State-of-the-art
RF Oscillators and Distribution.

FELs EUROPE, WS “Perspectives and Future Challenges in Optical and RF Synchronization Systems”

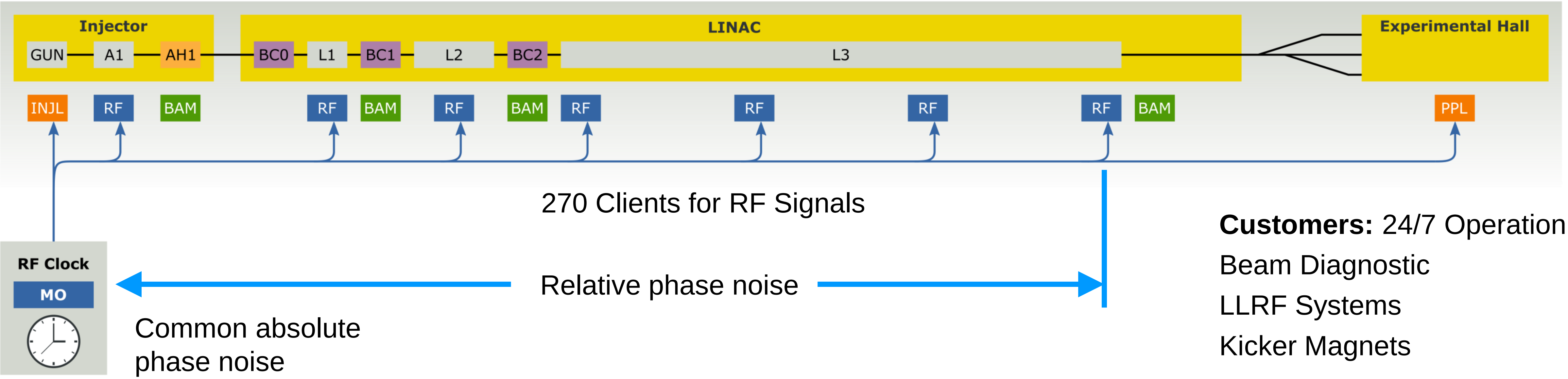
Dr. Frank Ludwig on behalf of the MSK, LbSynch team at DESY, WUT (Warsaw University)
Hamburg, Germany, 14.11.2023

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

RF-Synchronization – Overview Phase Distribution

- Typical XFEL, RF-synchronization system, Frequency: ~GHz, Length ~km:



270 Clients for RF Signals

Relative phase noise

Common absolute phase noise

Customers: 24/7 Operation
Beam Diagnostic
LLRF Systems
Kicker Magnets

- Sources of timing jitter short-term, long-term:

Short range 1 us…1ms:
PS, EMI, Electronics, Material Prop, …

Mid range 1ms…10s:
Acoustic, Fans, Seismic, Air/Water flow, …

Long range 10s … days:
Temperature, Humidity, Air Pressure,…

- Properties of a passive RF-cable distribution:

(+) Minor short-term jitter contribution

(+) Relatively low cost for small facilities

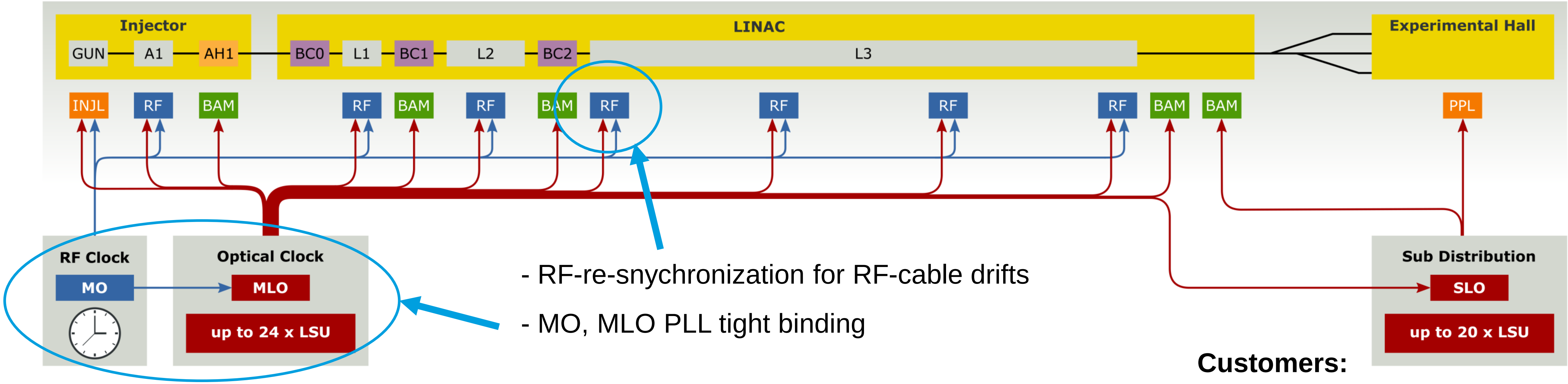
(--) Drift ~20fs/m/K **(T, RH, air pressure)** in the >10ps range

(--) Power loss **~3dB/100m** -> lower freq, ULN ampl. (>10dBm)

(--) EMC sensitive

RF-Synchronization – Overview Phase Distribution

- e.g. RF-synchronization in combination with an optical synchronization:



- RF-re-synchronization for RF-cable drifts

- MO, MLO PLL tight binding

Customers:

Injector laser, pump-probe

Bunch-Arrival Monitors (BAM)

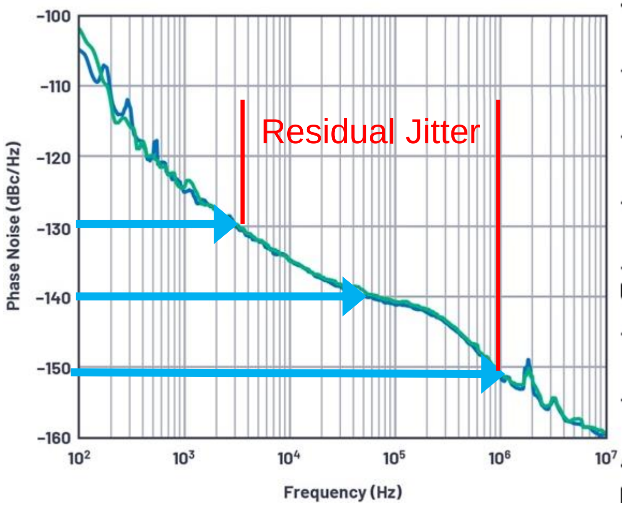
Laser-Pulse Arrival Monitors

- Absolute phase noise from MO and sub-systems with different noise BWs :

MO, MLO PLL
REFM-OPT

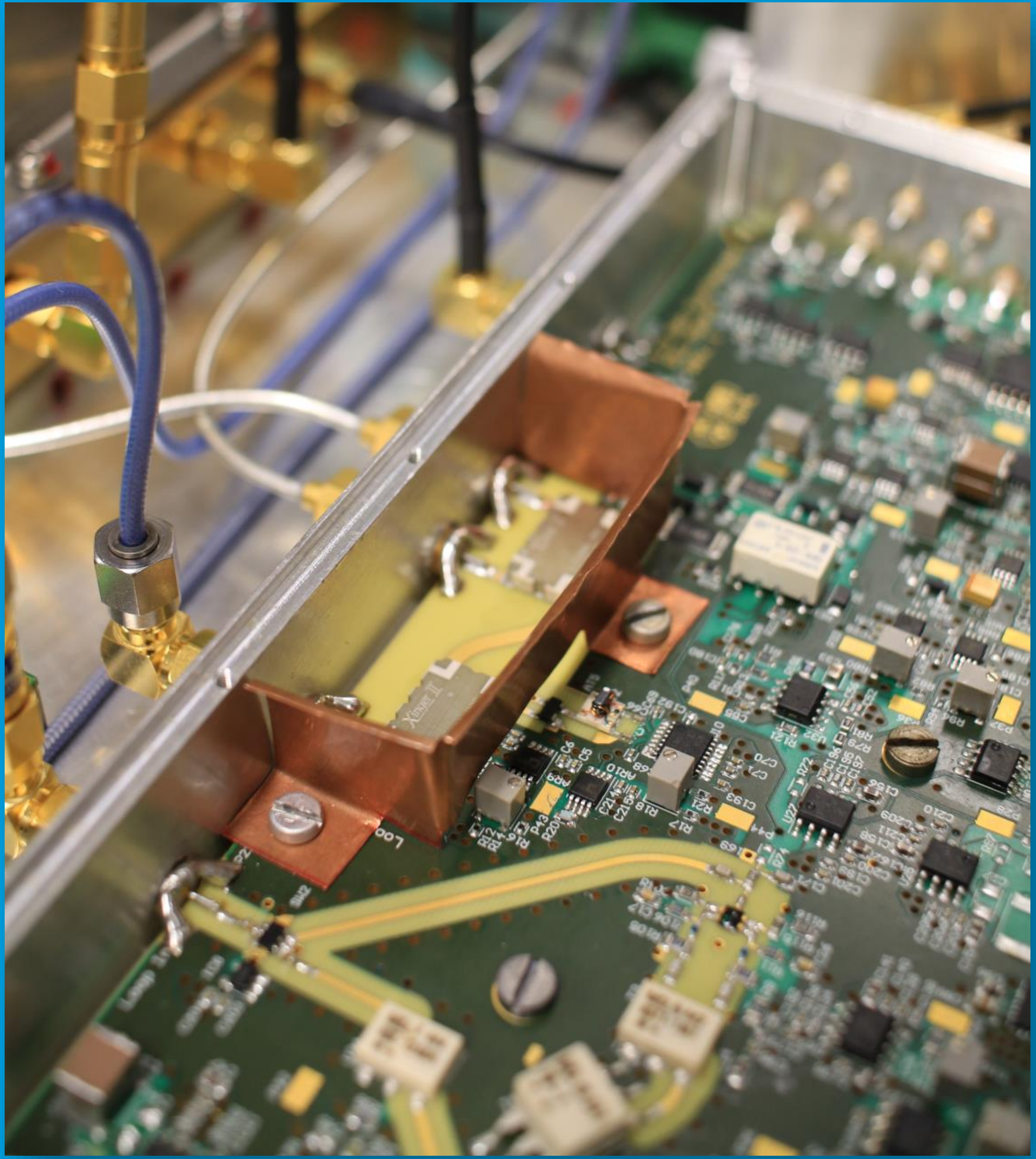
LLRF-System

BAMs



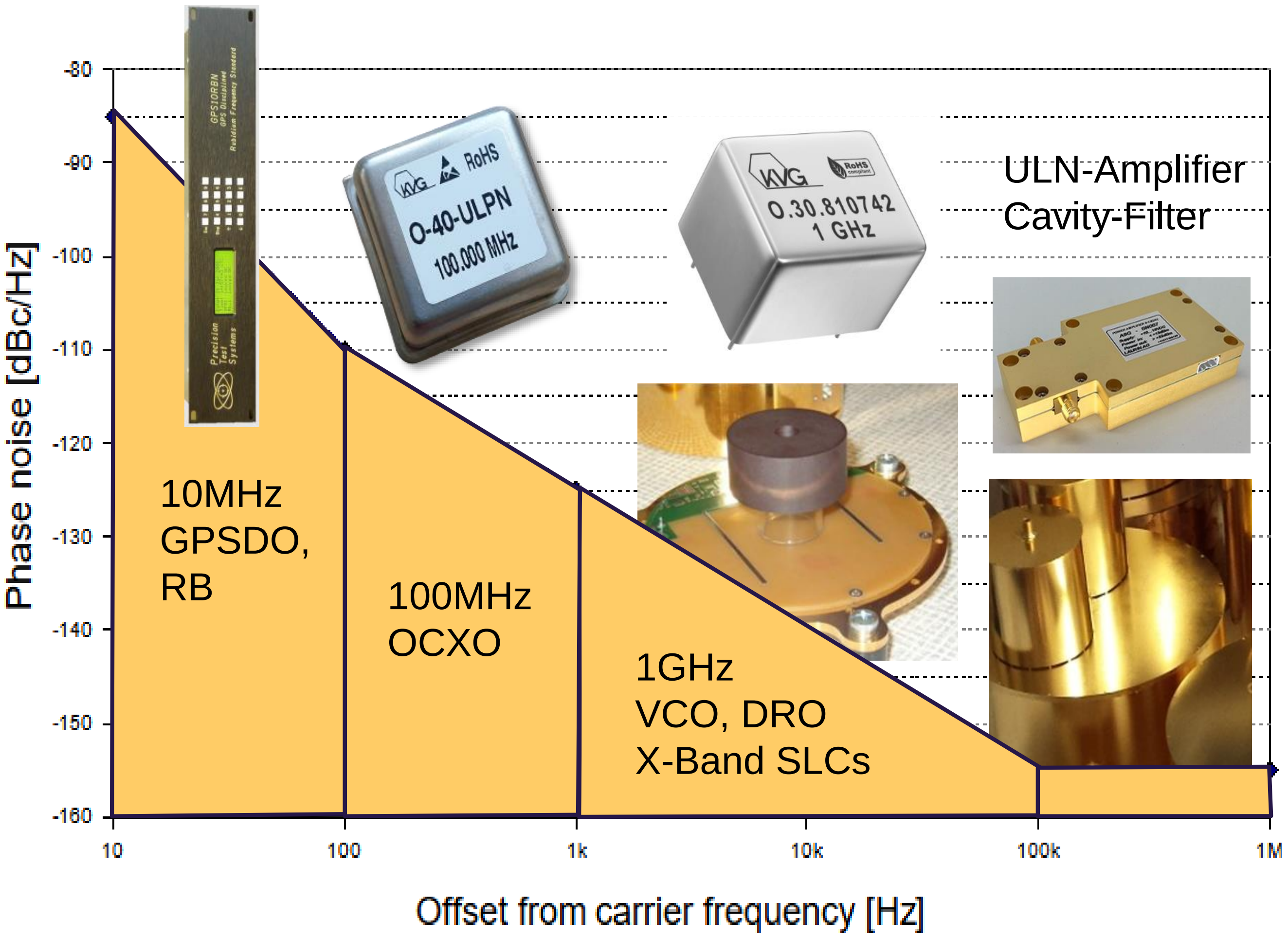
- Low 1/f-noise Main-Oscillator
- Low noise MLO
- Noise modelling, optimal BWs

RF-Oscillators

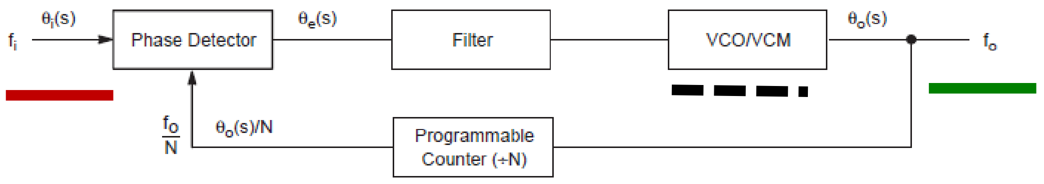


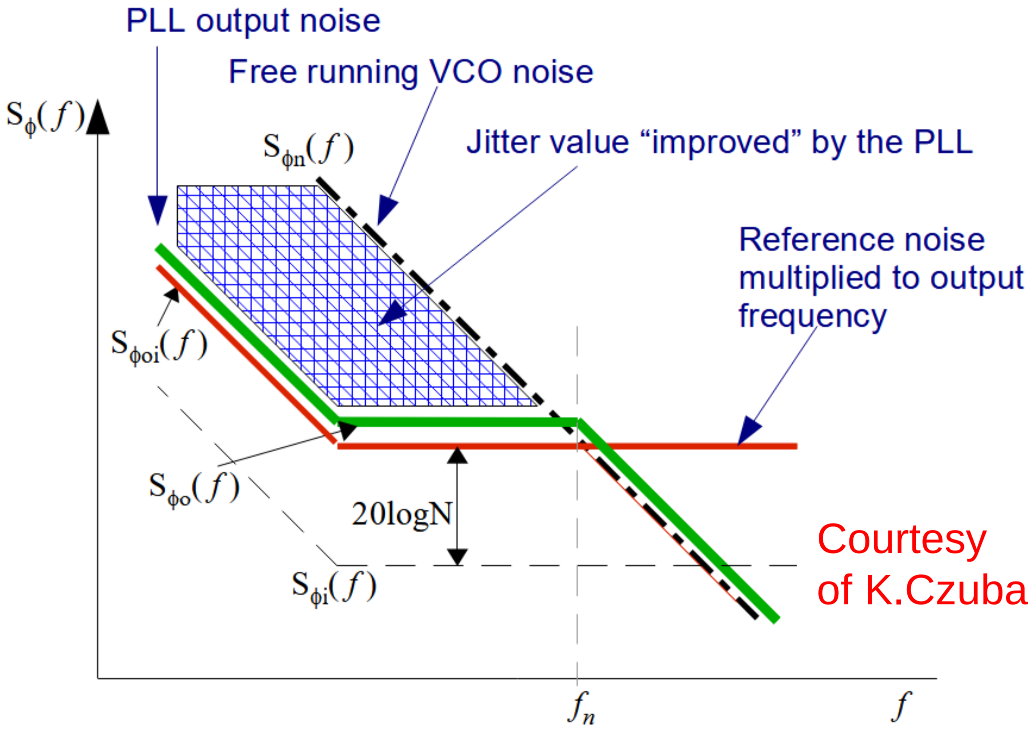
RF-Oscillators – Concepts for optimal Phase Noise

- Combination of different oscillators :



- Phase-Lock-Loop (PLL) Synthesizer :

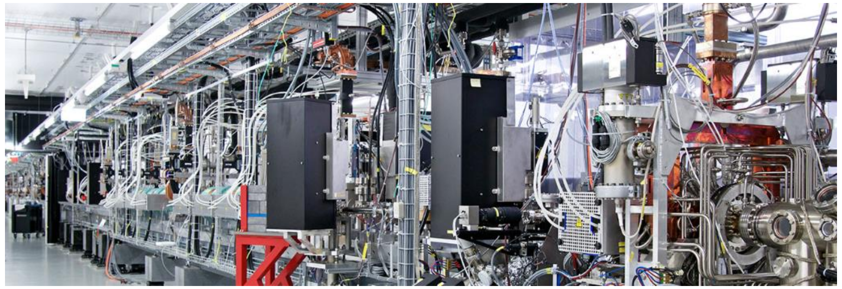


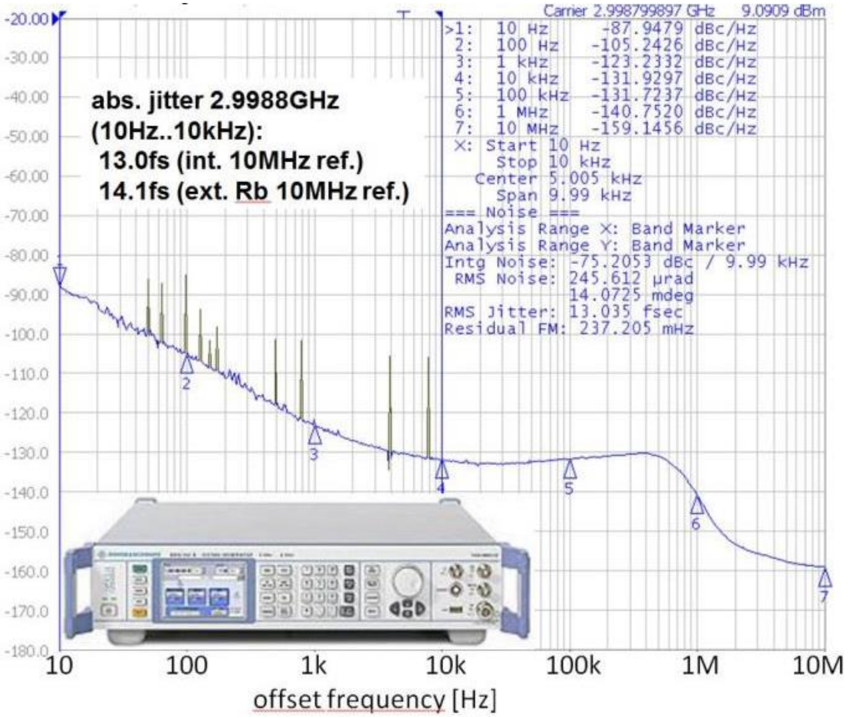


Courtesy of K.Czuba

RF-Oscillators – State-of-the-art (commercial) Examples

- SwissFEL - (SMA100A, commercial) :





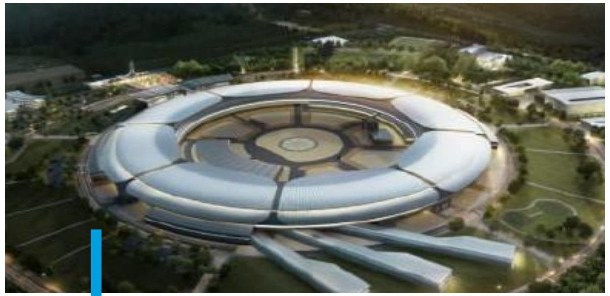
Carrier 2.998799897 GHz 9.0909 dBm

```
>1:  10 Hz     -87.9479 dBc/Hz
 2:  100 Hz   -105.2426 dBc/Hz
 3:  1 kHz    -123.2332 dBc/Hz
 4:  10 kHz   -131.9297 dBc/Hz
 5:  100 kHz  -131.7237 dBc/Hz
 6:  1 MHz    -140.7520 dBc/Hz
 7:  10 MHz   -159.1456 dBc/Hz
 X: Start 10 Hz
     Stop 10 kHz
   Center 5.005 kHz
     Span 9.99 kHz
=== Noise ===
Analysis Range X: Band Marker
Analysis Range Y: Band Marker
Intg Noise: -75.2053 dBc / 9.99 kHz
 RMS Noise: 245.612 µrad
            14.0725 mdeg
RMS Jitter: 13.035 fsec
Residual FM: 237.205 mHz
```

abs. jitter 2.9988GHz (10Hz..10kHz):
13.0fs (int. 10MHz ref.)
14.1fs (ext. Rb 10MHz ref.)

"REFERENCE DISTRIBUTION AND SYNCHRONIZATION SYSTEM FOR SwissFEL: CONCEPT AND FIRST RESULTS", S. Hunziker et. al., IBIC2014, CA, USA MOCZB2

- SRs (SMA100B, Korea-4GSR, DESY-Petra III, ARES …)



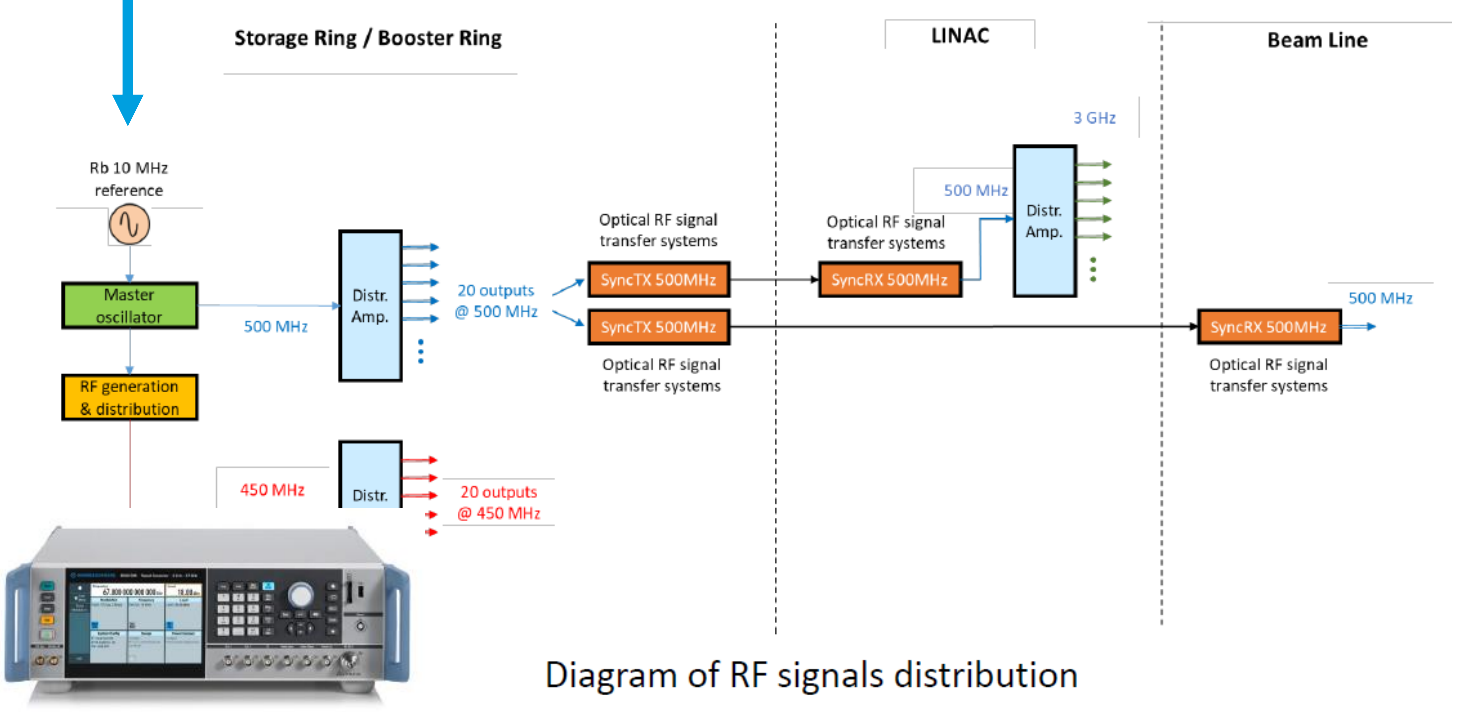


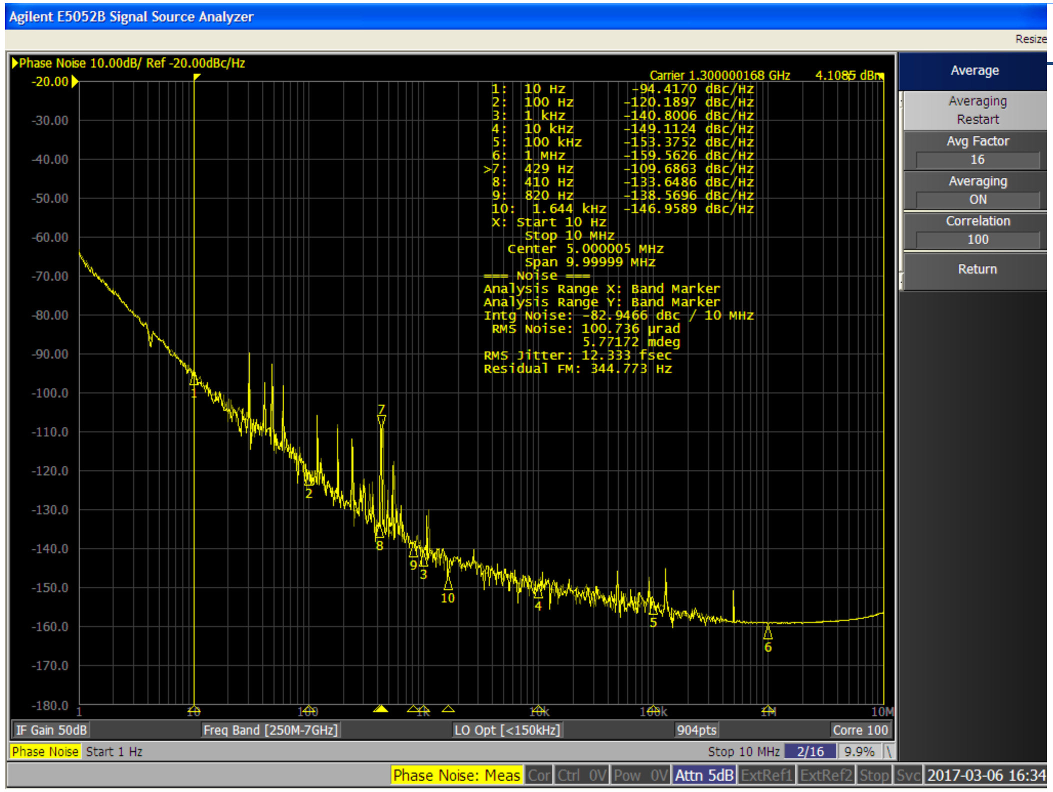
Diagram of RF signals distribution

18.7 fs rms @ [10kHz,5MHz]

"Progress in LLRF system development for Korea-4GSR", Yong-SeokLee, Pohang Accelerator Laboratory, Korea LLRF2023

RF-Oscillators – State-of-the-art (very high performance)

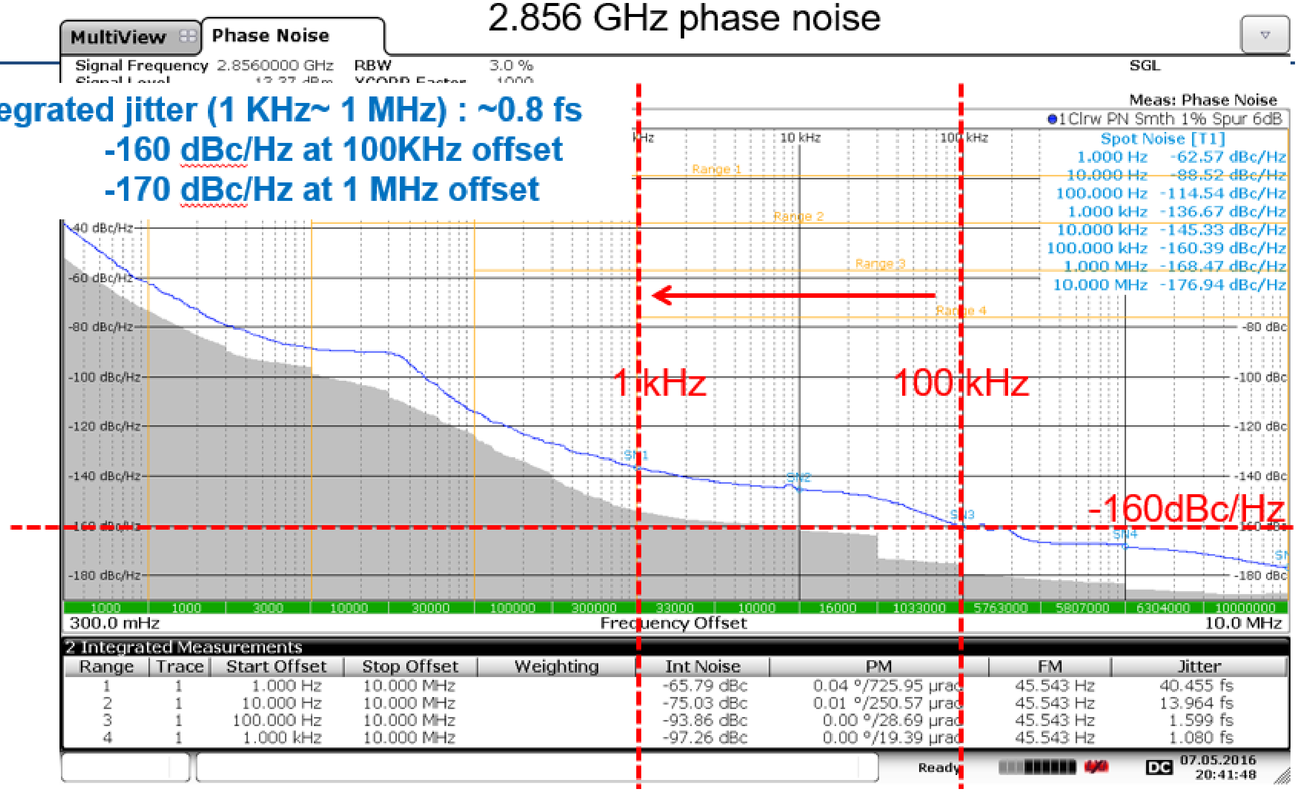
- LCLS-II (1300MHz via 8x162.5 GMXO) :



```
Carrier 1.300000168 GHz      4.1085 dBm
  1:   10 Hz          -94.4170 dBc/Hz
  2:   100 Hz        -120.1897 dBc/Hz
  3:   1 kHz         -140.8006 dBc/Hz
  4:   10 kHz        -149.1124 dBc/Hz
  5:   100 kHz       -153.3752 dBc/Hz
  6:   1 MHz         -159.5626 dBc/Hz
 >7:   429 Hz        -109.6863 dBc/Hz
  8:   410 Hz        -133.6486 dBc/Hz
  9:   820 Hz        -138.5696 dBc/Hz
 10:   1.644 kHz     -146.9589 dBc/Hz
  X: Start 10 Hz
       Stop 10 MHz
     Center 5.000005 MHz
       Span 9.99999 MHz
=== Noise ===
Analysis Range X: Band Marker
Analysis Range Y: Band Marker
Intg Noise: -82.9466 dBc / 10 MHz
 RMS Noise: 100.736 µrad
            5.77172 mdeg
RMS Jitter: 12.333 fsec
Residual FM: 344.773 Hz
```

MO Integral jitter:
10Hz-10MHz is 12.3fs.
100Hz-10kHz is 3.5fs [spec is 10fs]

- PAL-XFEL (DRO-based):



Integrated jitter (1 KHz~ 1 MHz) : ~0.8 fs
-160 dBc/Hz at 100KHz offset
-170 dBc/Hz at 1 MHz offset

```
Spot Noise [T1]
    1.000 Hz   -62.57 dBc/Hz
   10.000 Hz   -88.52 dBc/Hz
  100.000 Hz  -114.54 dBc/Hz
    1.000 kHz -136.67 dBc/Hz
   10.000 kHz -145.33 dBc/Hz
  100.000 kHz -160.39 dBc/Hz
    1.000 MHz -168.47 dBc/Hz
   10.000 MHz -176.94 dBc/Hz
```

2 Integrated Measurements

Range	Trace	Start Offset	Stop Offset	Weighting	Int Noise	PM	FM	Jitter
1	1	1.000 Hz	10.000 MHz		-65.79 dBc	0.04 °/725.95 µrad	45.543 Hz	40.455 fs
2	1	10.000 Hz	10.000 MHz		-75.03 dBc	0.01 °/250.57 µrad	45.543 Hz	13.964 fs
3	1	100.000 Hz	10.000 MHz		-93.86 dBc	0.00 °/28.69 µrad	45.543 Hz	1.599 fs
4	1	1.000 kHz	10.000 MHz		-97.26 dBc	0.00 °/19.39 µrad	45.543 Hz	1.080 fs

MO Integral jitter:
10Hz-10MHz is 13.96fs.
100Hz-1MHz is 1.48fs

“RF reference distribution and operation experiences in PAL-XFEL”, Chang-Ki Min, Pohang Accelerator Laboratory,Korea LLRF2023

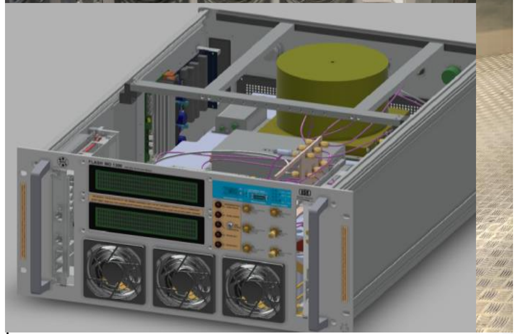
RF-Oscillators – FLASH Evolution <100fs, <20fs, <2fs

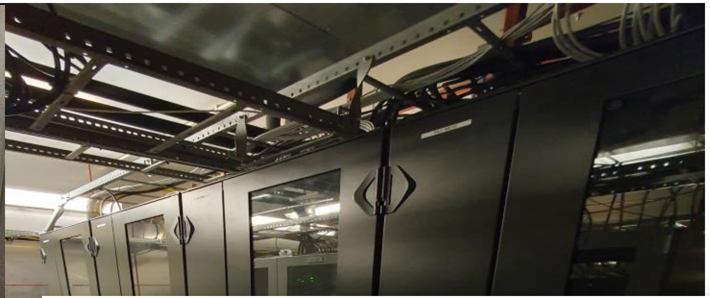
- FLASH Main-Oscillator (MO):

FLASH:
4fs [>1kHz],
81fs [10Hz-10MHz]
5 Racks battery buffered
2 redundant MOs

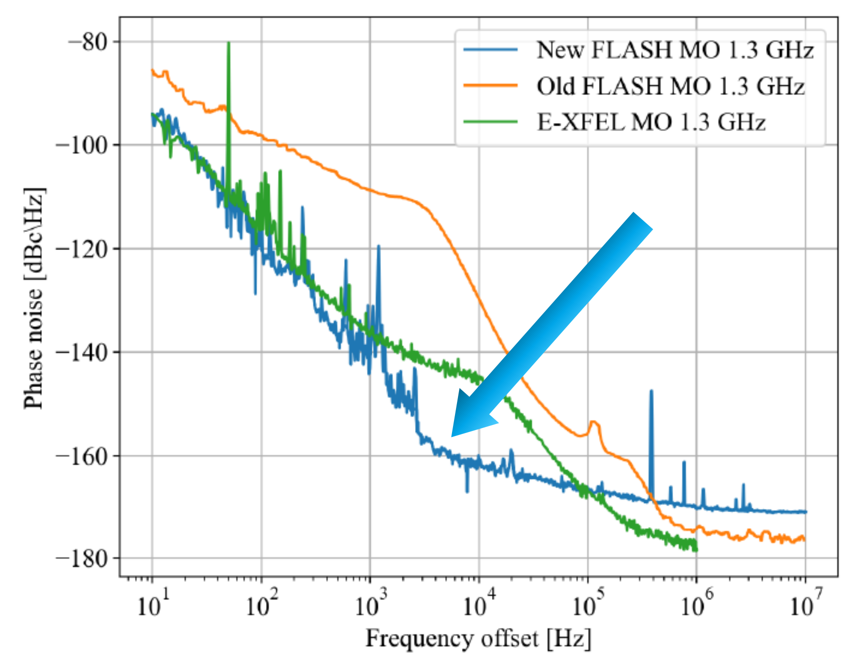
Phase jumps increased after 10 years of operation ->

XFEL
< 20fs [10Hz-10MHz]
3 Racks
3 redundant MOs
Much less modules
Monitoring Diagnostic





FLASH
< 2fs [100Hz-10MHz]
3 Racks
2 redundant MOs
XFEL & FLASH crate compatible
External USV



2008

2018

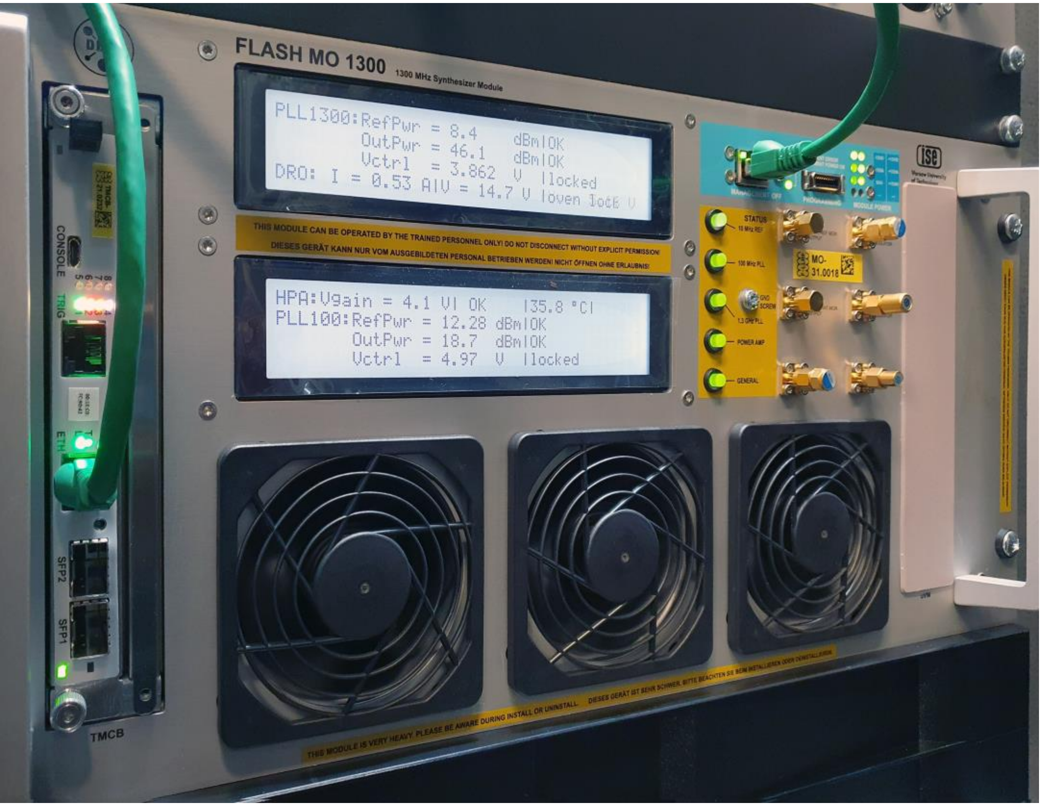
2022

Courtesy
of H. Pryschelski, K. Czuba

MO: Sub – 1fs Reference for FLASH

- FLASH new Main Oscillator :

1.3GHz, +46dBm, Health monitoring



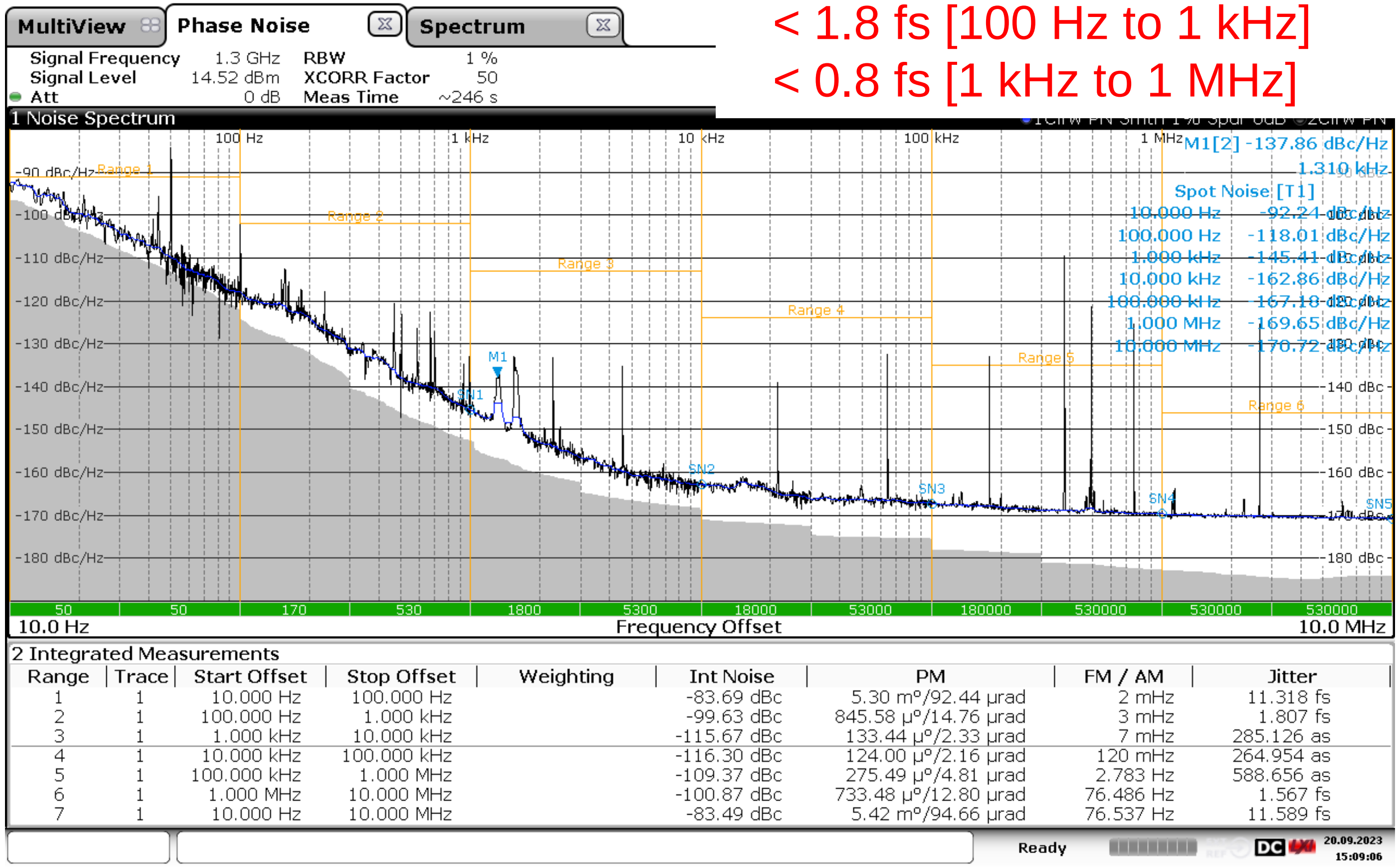
Under license from DESY

KVG Quartz Crystal Technology GmbH
info@kvg-gmbh.de

Quartz Crystal Technology GmbH

- Absolute Phase-noise :

Integrated Jitter:
< 12 fs [10 Hz to 100 Hz]
< 1.8 fs [100 Hz to 1 kHz]
< 0.8 fs [1 kHz to 1 MHz]



Signal Frequency 1.3 GHz
Signal Level 14.52 dBm
Att 0 dB
RBW 1 %
XCORR Factor 50
Meas Time ~246 s

M1[2] -137.86 dBc/Hz
1.310 kHz

Spot Noise [T1]

10.000 Hz	-92.24 dBc/Hz
100.000 Hz	-118.01 dBc/Hz
1.000 kHz	-145.41 dBc/Hz
10.000 kHz	-162.86 dBc/Hz
100.000 kHz	-167.18 dBc/Hz
1.000 MHz	-169.65 dBc/Hz
10.000 MHz	-170.72 dBc/Hz

2 Integrated Measurements

Range	Trace	Start Offset	Stop Offset	Weighting	Int Noise	PM	FM / AM	Jitter
1	1	10.000 Hz	100.000 Hz		-83.69 dBc	5.30 m°/92.44 µrad	2 mHz	11.318 fs
2	1	100.000 Hz	1.000 kHz		-99.63 dBc	845.58 µ°/14.76 µrad	3 mHz	1.807 fs
3	1	1.000 kHz	10.000 kHz		-115.67 dBc	133.44 µ°/2.33 µrad	7 mHz	285.126 as
4	1	10.000 kHz	100.000 kHz		-116.30 dBc	124.00 µ°/2.16 µrad	120 mHz	264.954 as
5	1	100.000 kHz	1.000 MHz		-109.37 dBc	275.49 µ°/4.81 µrad	2.783 Hz	588.656 as
6	1	1.000 MHz	10.000 MHz		-100.87 dBc	733.48 µ°/12.80 µrad	76.486 Hz	1.567 fs
7	1	10.000 Hz	10.000 MHz		-83.49 dBc	5.42 m°/94.66 µrad	76.537 Hz	11.589 fs

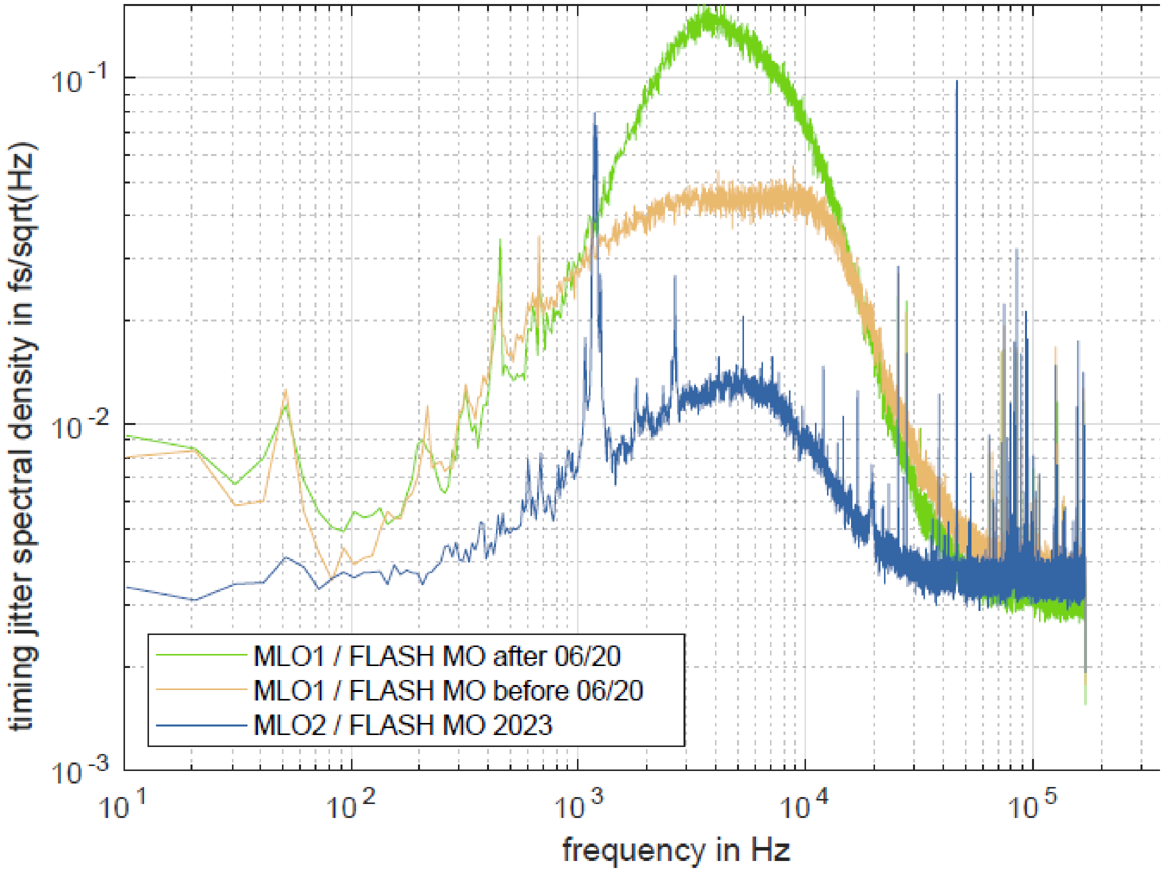
15:09:06 20.09.2023

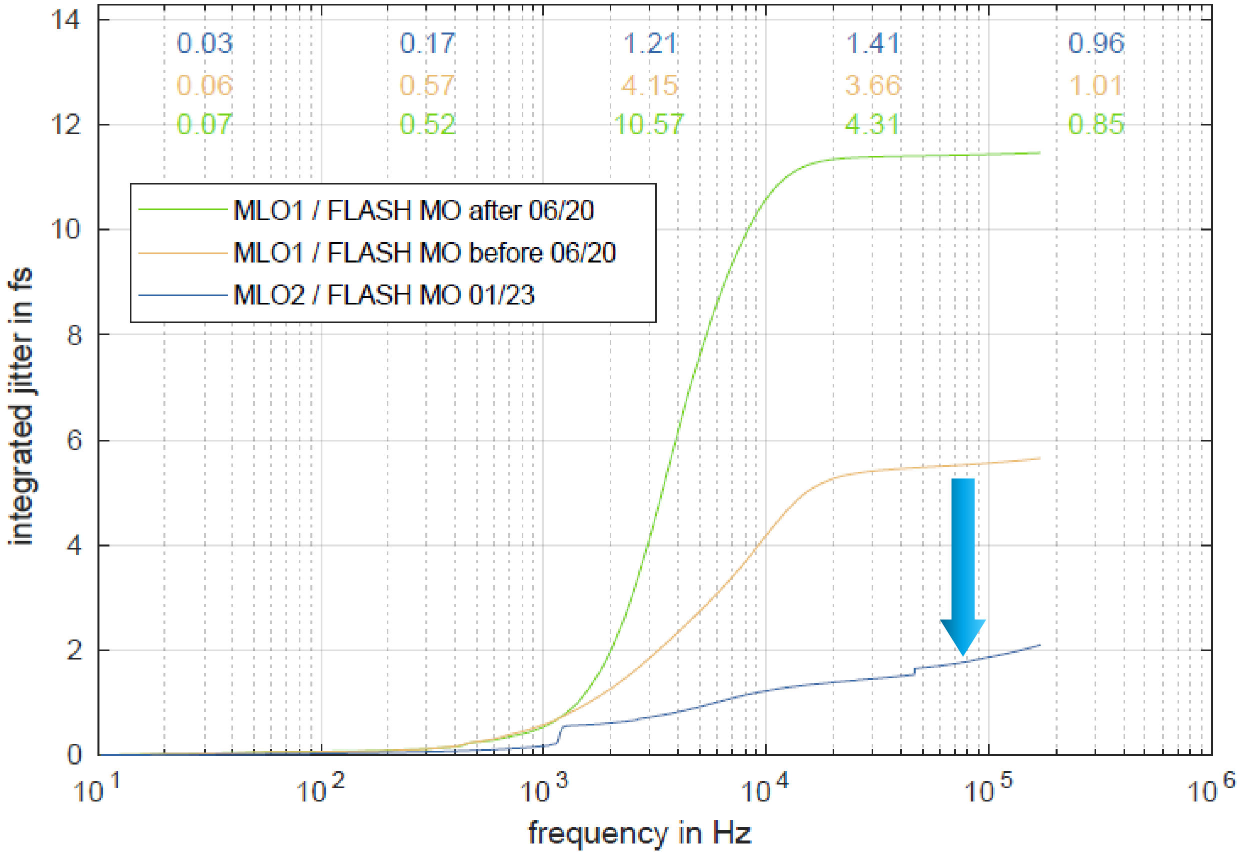
- **Improvement of int. jitter from 38 fs to 1.8 fs [100Hz, 1MHz]**
- fs-laser systems locked to the reference show significant improvement

MO-MLO Lock: Residual Noise

- MO-MLO in-loop residual phase noise (tight lock, BW limited by fiber-stretcher) :

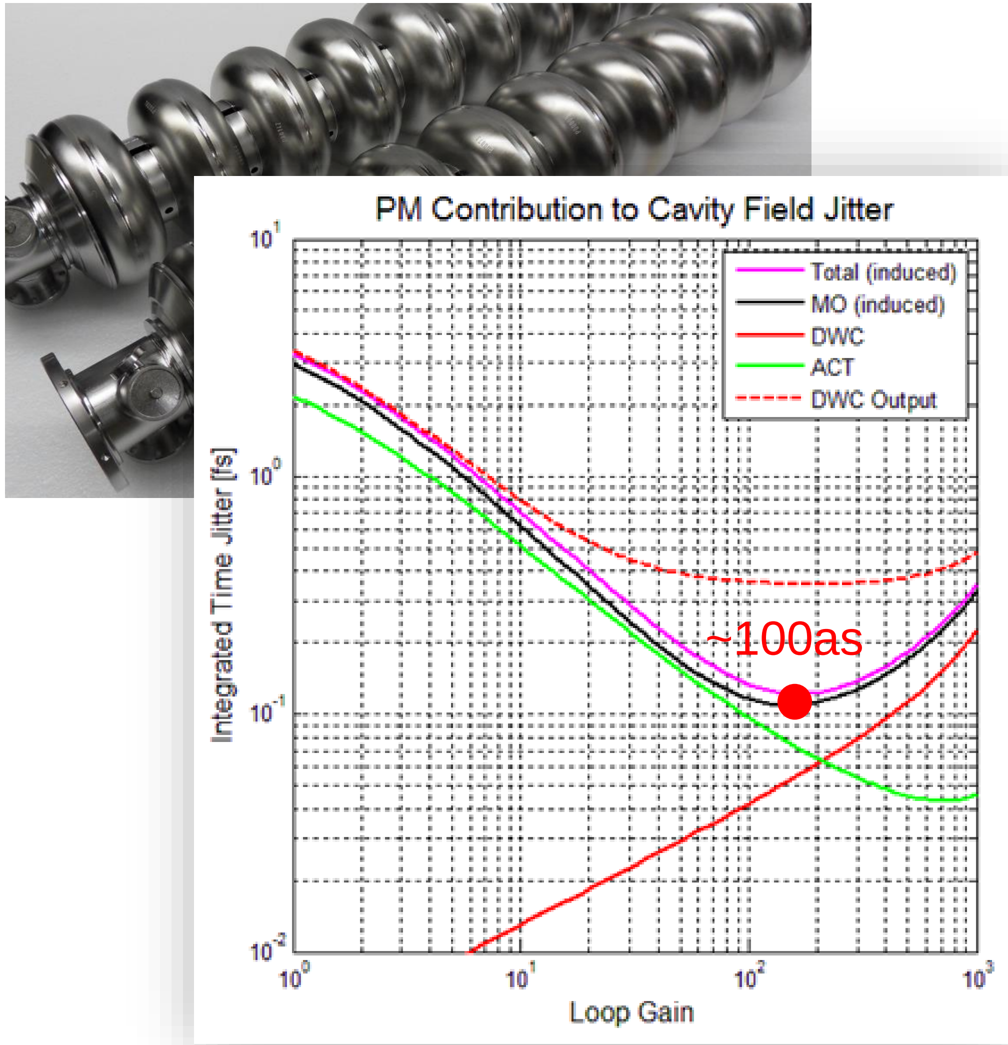
Courtesy
of T.Lamb





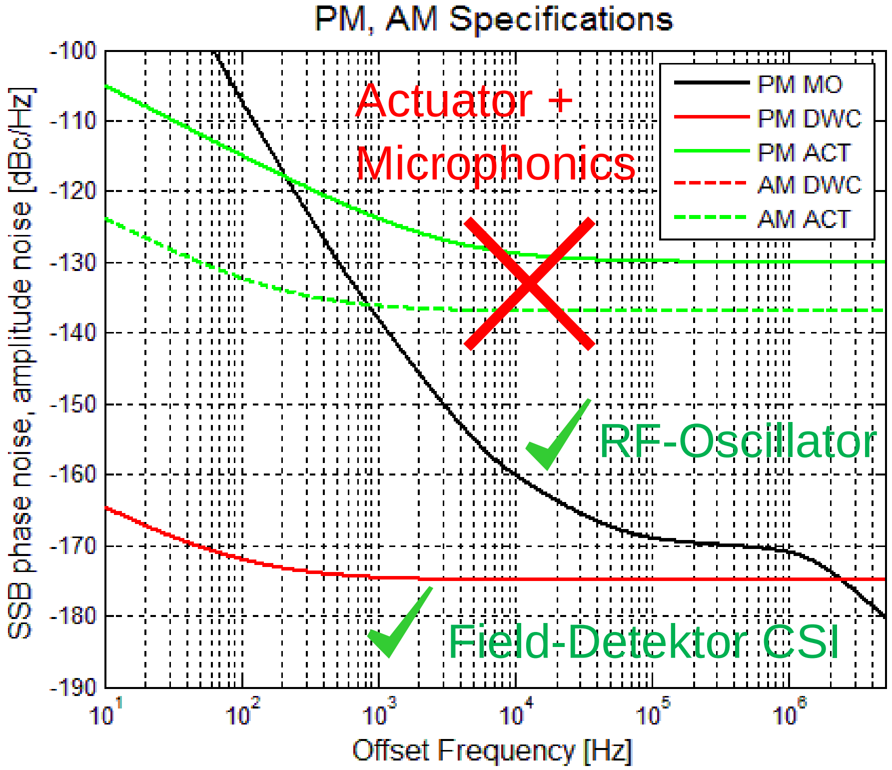
Towards as-Precision – MO Application LLRF

- SRF-Cavity (1.3GHz, Q_L $3\cdot10^6$, BW 200Hz) :



- LLRF Component Requirements :

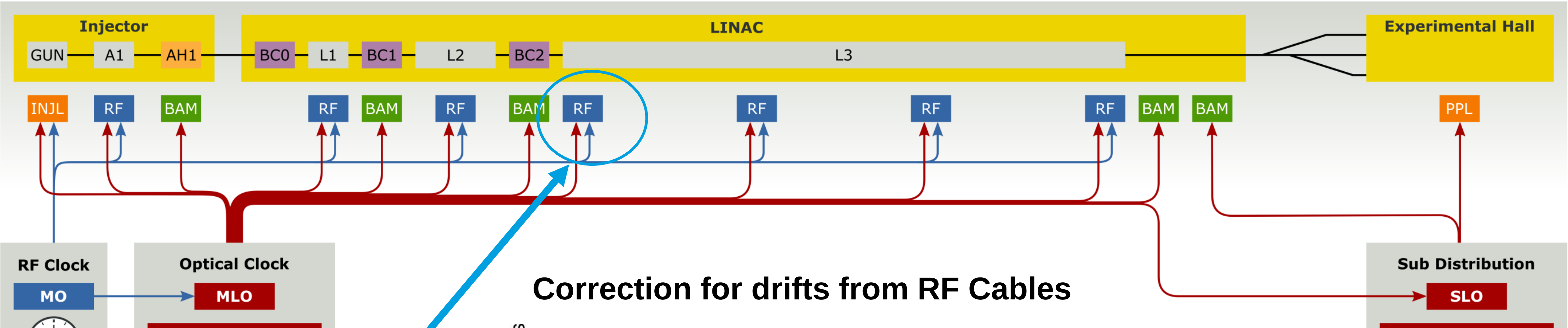
Master reference (MO) : <-170dBc/Hz
Actuator chain (ACT) : <-140dBc/Hz
Field detectors (DWC) : <-175dBc/Hz (-150dBc/Hz)



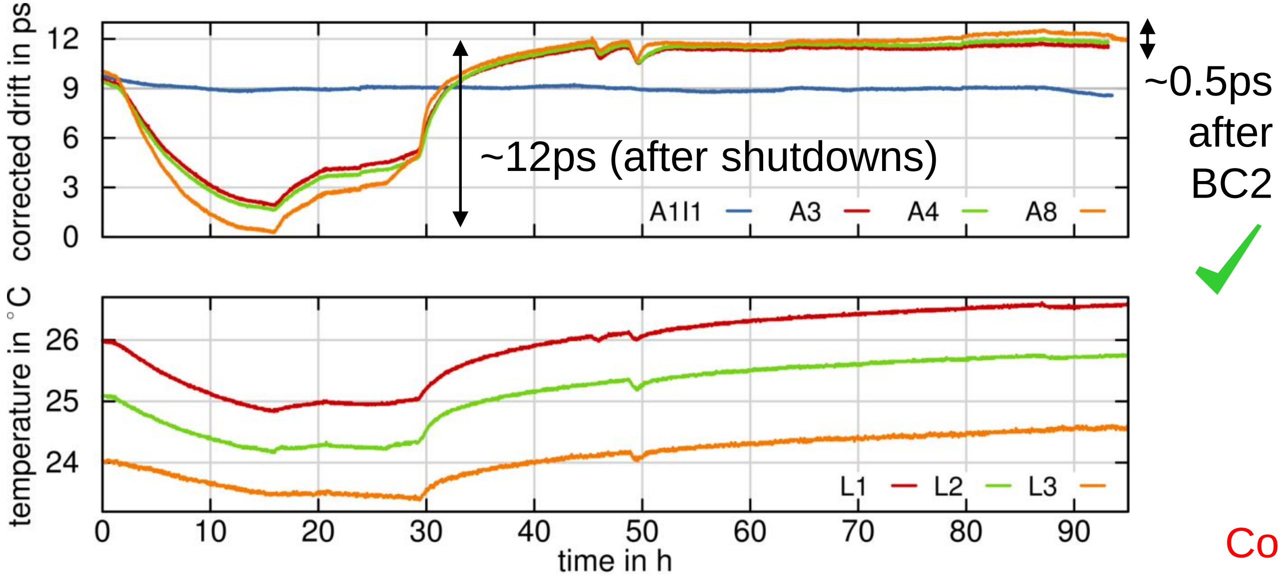
RF-Distribution

RF-Distribution – Passive – optical re-synchronized

- e.g. RF-synchronization in combination with an optical synchronization:



Correction for drifts from RF Cables



~12ps (after shutdowns)

~0.5ps after BC2 ✓

Courtesy: T. Lamb

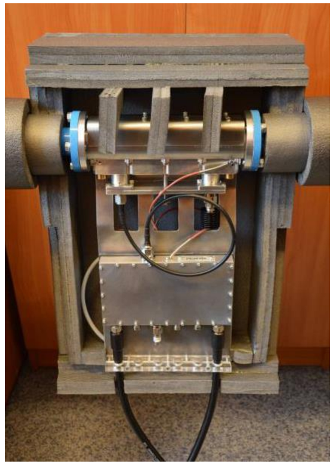
- Laser-to-RF phase detector :

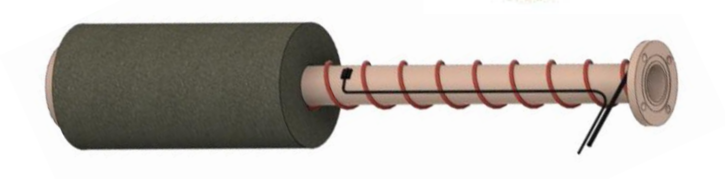
RF-Distribution – Passive, temp. and gas stablized

- ESS RF Phase synchronization system:
  - Single 1/5” coax rigid line for 352MHz and 704 MHz
  - 58 RF-TapPoints, 294 outputs, + 17dBm
  - Temperature controlled line with **0.015 deg p-p**
  - Temperature controlled coupler TapPoints with **0.1 deg**
  - Nitrogen gas to remove humidity, pressure stabilized **1mbar**

- Single 1/5“ coax riged line :

- TapPoint coupler / Cable heater :



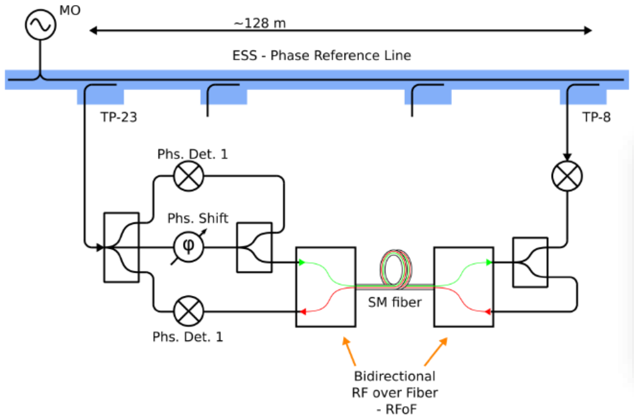


- Gas pressure influence on phase :

0.11 deg / mbar for 600m
achieved +/-1mbar pressure stability
quite sensitive

“Performance Summary of the ESS Phase Reference Line”, K. Czuba, Korea LLRF2023

- Out-of-loop verification **0.12 deg** pp in spec :



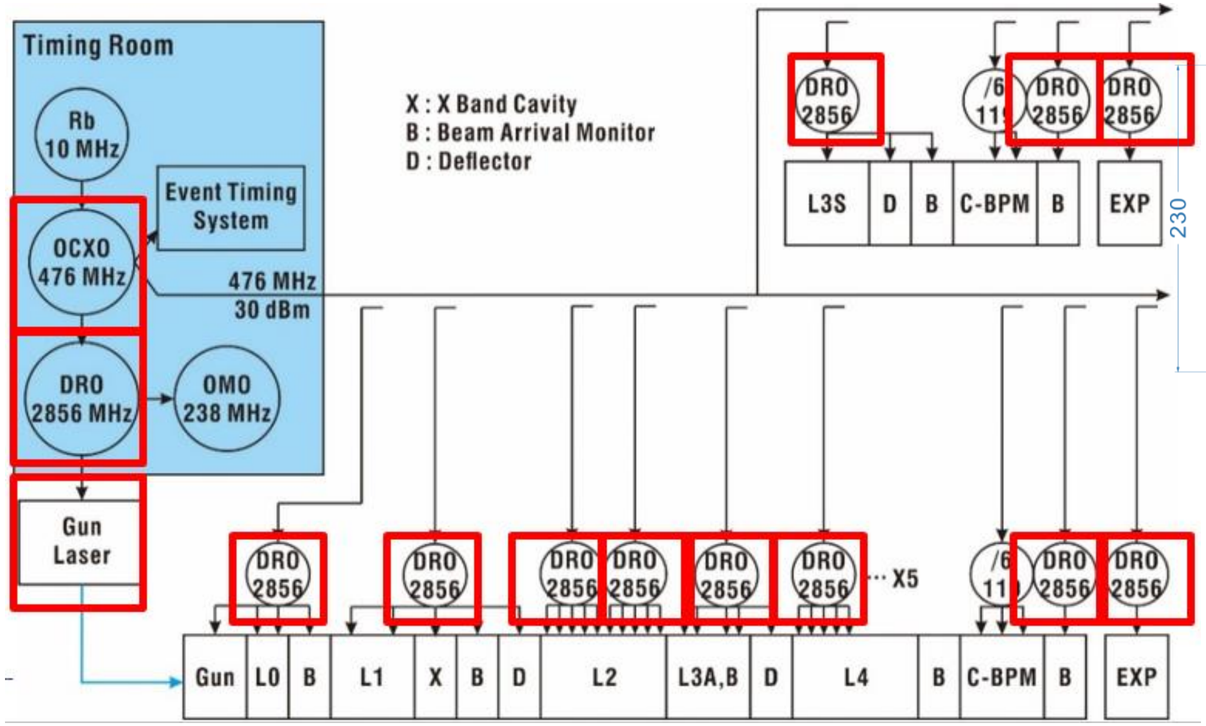
Drift of PRL seems better than tests (TBD)

RF-Distribution – Passive – temperature stabilized

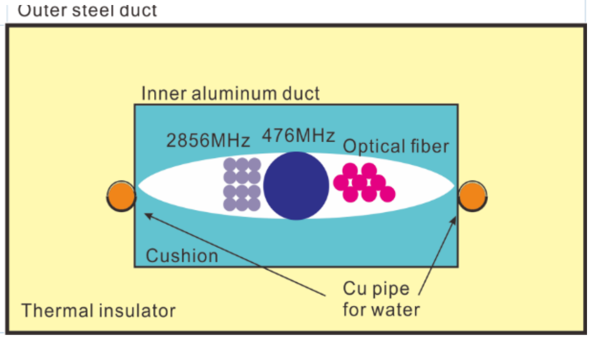
- PAL-XFEL (Pohang) RF-synchronization system (2.856GHz RF), ~1.5 km):

“RF reference distribution and operation experiences in PAL-XFEL”, Chang-Ki Min, Pohang Accelerator Laboratory,Korea LLRF2023

- Single cellflex line for 476MHz, +30dBm (Drift transport)
- Local re-synchronization via PLLs and DROs to S-Band (Jitter transport)
- Temperature controlled line with water pipes to **0.01 deg / day**



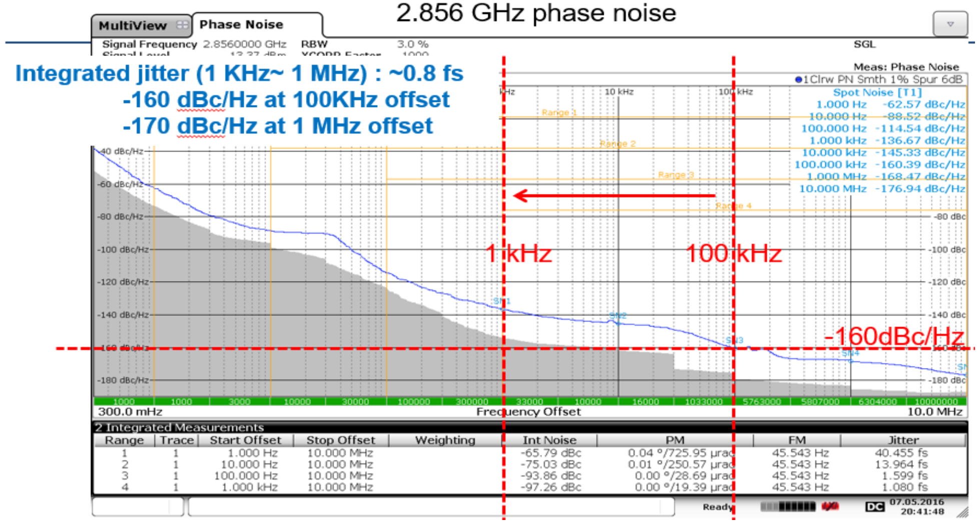
Duct cross-section



Main line (cover open)

RF-Distribution – Passive – temperature stabilized

- Short-term DRO, PLL performance:



2.856 GHz phase noise

Integrated jitter (1 KHz~ 1 MHz) : ~0.8 fs

-160 dBc/Hz at 100KHz offset

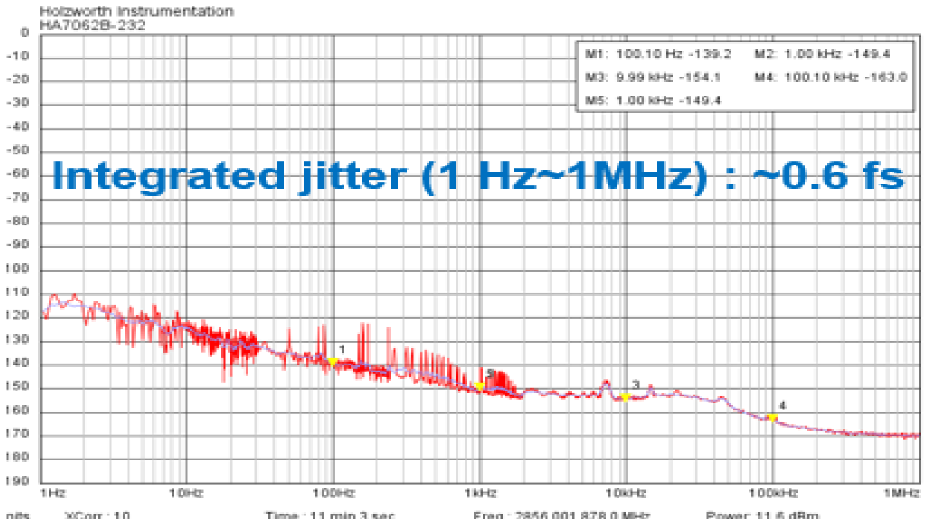
-170 dBc/Hz at 1 MHz offset

Spot Noise [T1]

1.000 Hz	-62.57 dBc/Hz
10.000 Hz	-88.52 dBc/Hz
100.000 Hz	-114.54 dBc/Hz
1.000 kHz	-136.67 dBc/Hz
10.000 kHz	-145.33 dBc/Hz
100.000 kHz	-160.39 dBc/Hz
1.000 MHz	-168.47 dBc/Hz
10.000 MHz	-176.94 dBc/Hz

2 Integrated Measurements

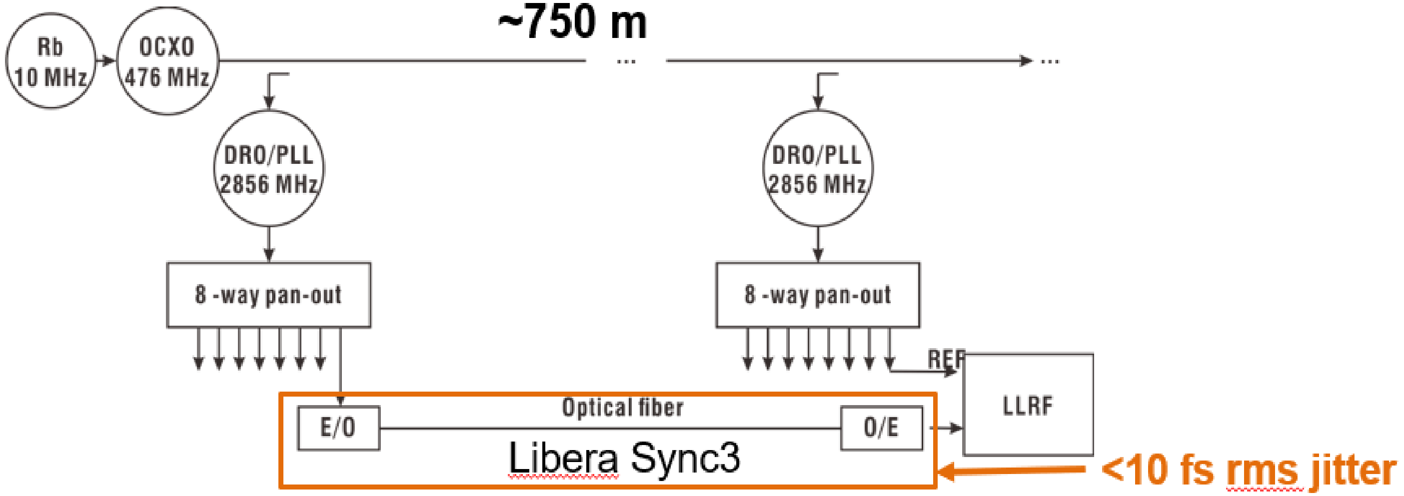
Range	Trace	Start Offset	Stop Offset	Weighting	Int Noise	PM	FM	Jitter
1	1	1.000 Hz	10.000 MHz		-65.79 dBc	0.04 °/725.95 µrad	45.543 Hz	40.455 fs
2	1	10.000 Hz	10.000 MHz		-75.03 dBc	0.01 °/250.57 µrad	45.543 Hz	13.964 fs
3	1	100.000 Hz	10.000 MHz		-93.86 dBc	0.00 °/28.69 µrad	45.543 Hz	1.599 fs
4	1	1.000 kHz	10.000 MHz		-97.26 dBc	0.00 °/19.39 µrad	45.543 Hz	1.080 fs



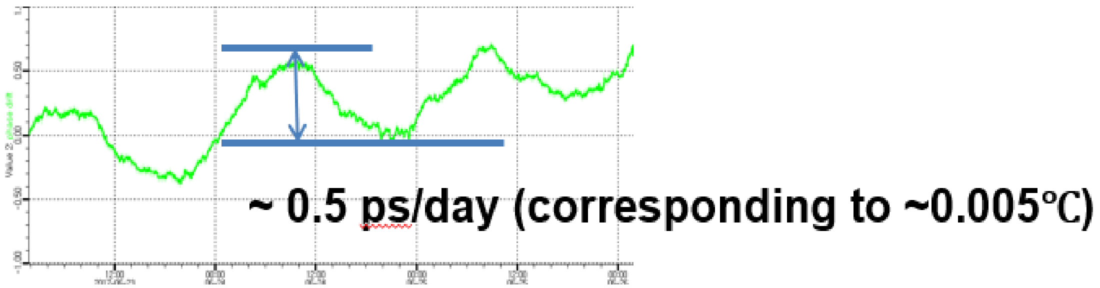
Integrated jitter (1 Hz~1MHz) : ~0.6 fs

- Long-term performance / verification:

“RF reference distribution and operation experiences in PAL-XFEL”, Chang-Ki Min, Pohang Accelerator Laboratory,Korea LLRF2023



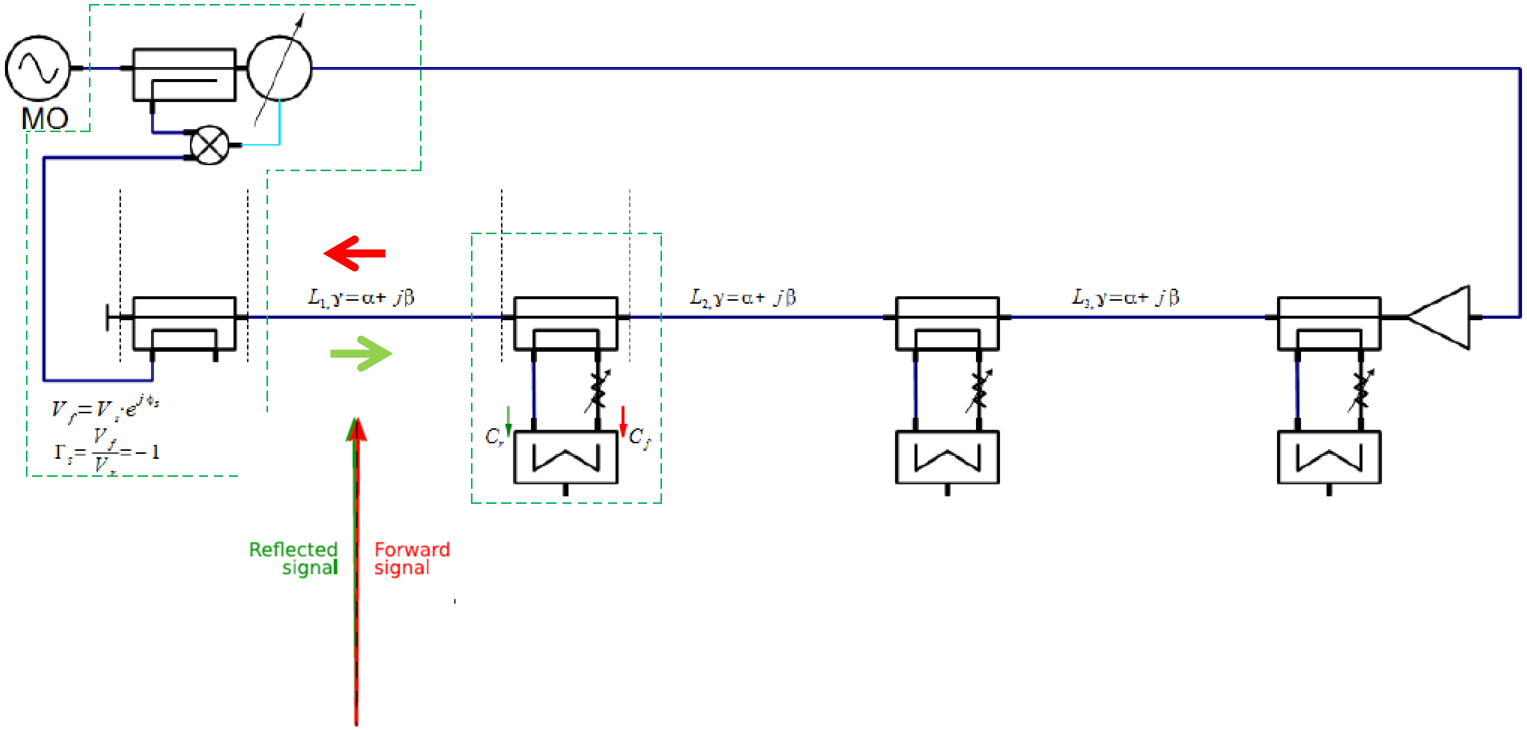
<10 fs rms jitter

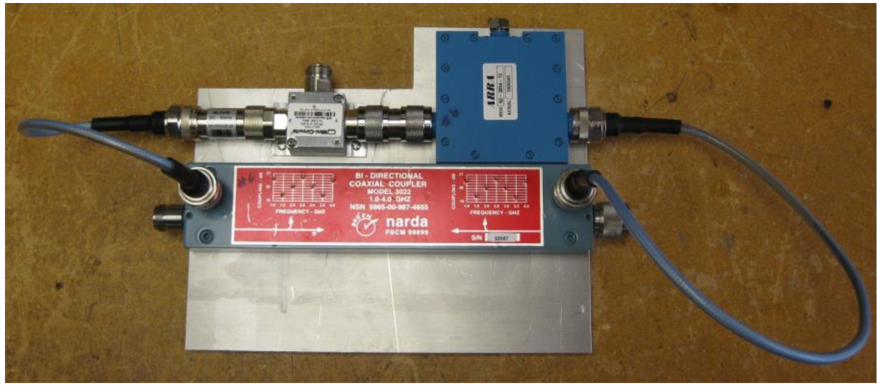


~ 0.5 ps/day (corresponding to ~0.005℃)

1ps_pp, 3 days, 750m -> 44fs/day/100m

RF-Distribution – Interferometer Basics

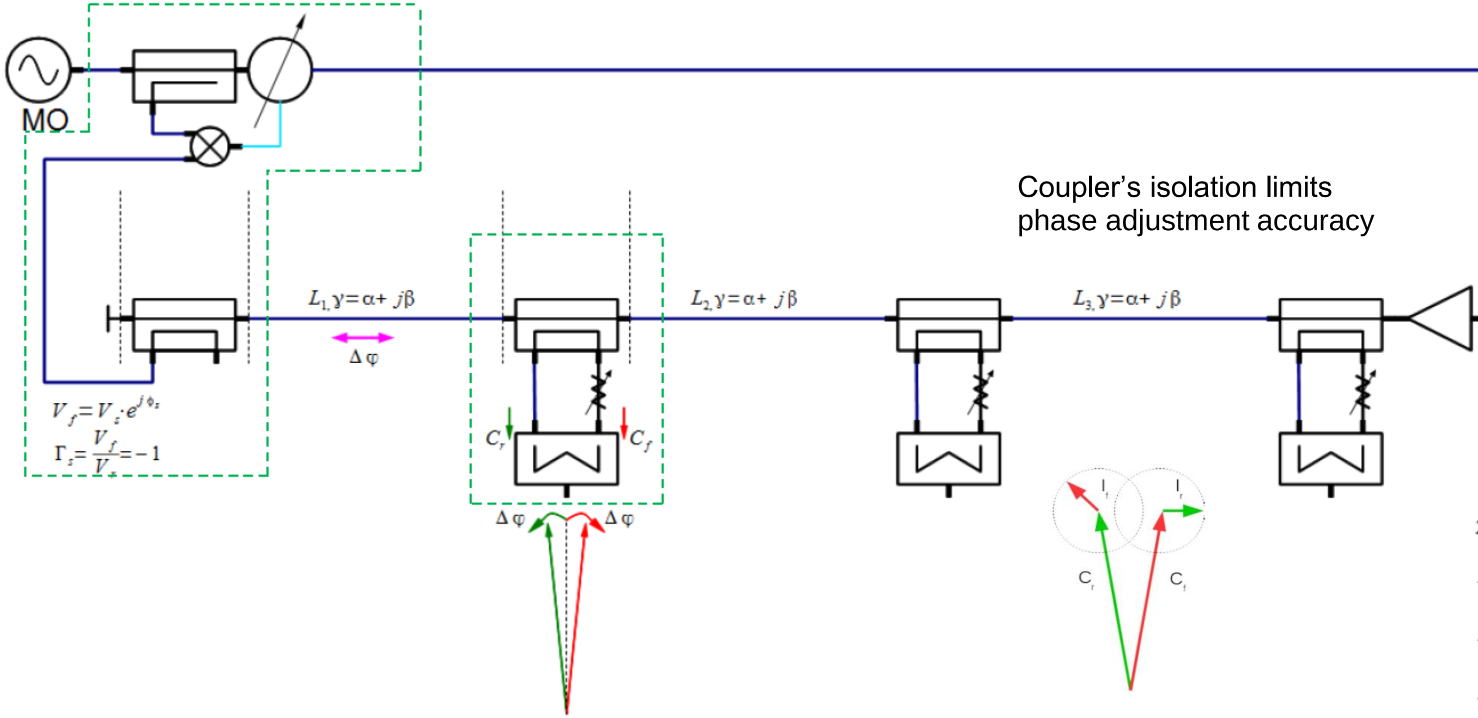




- Conditions:
  - Constant phase shift of the short – fixed by the feedback loop
  - Equal signals at the combiner inputs – attenuation and phase adjustments
  - Properly set distance between short and TapPoint (L1, L2, L3)

Idea of phase averaging reference line by J. Frisch, D. Brown, and E. Cisneros (paper titled, "*Performance of the Prototype NLC RF Distribution System*"), continued by Brian Chase and Ed Cullerton („*Reference Line Presentation*", LLRF 2011)

RF-Distribution – Interferometer Basics

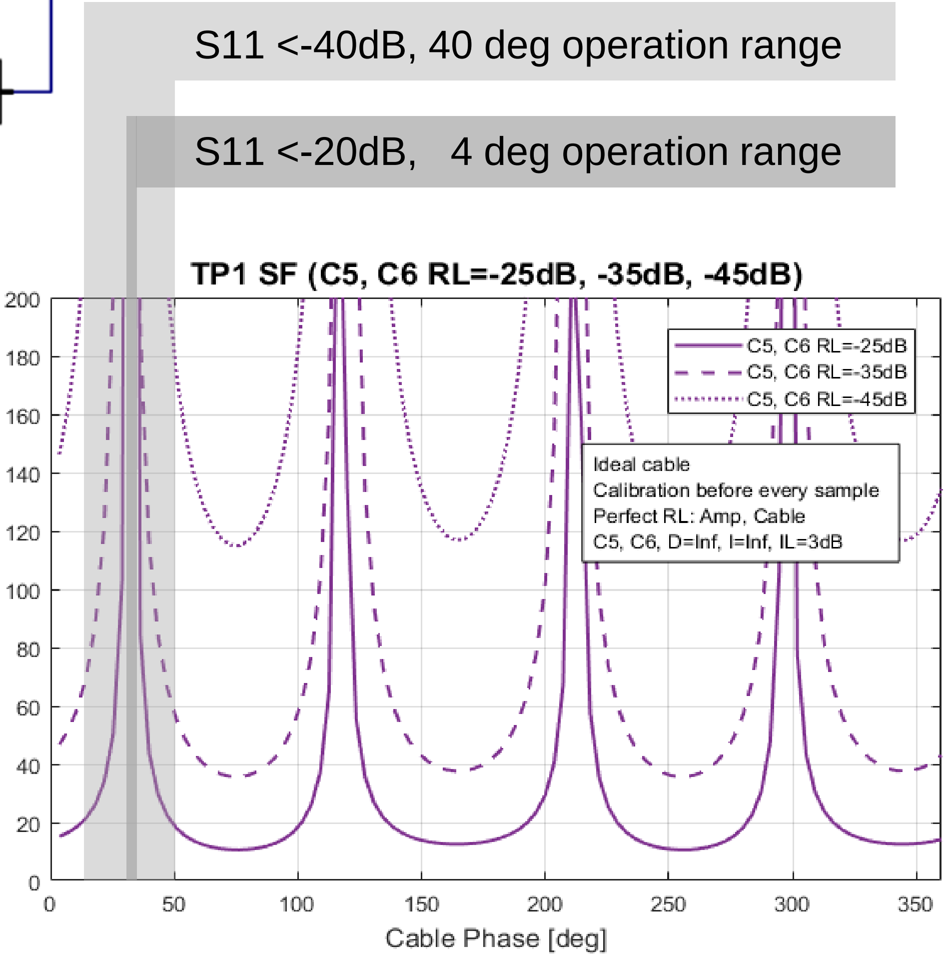


Coupler’s isolation limits
phase adjustment accuracy

- Suppression factor SF(S11):

S11 <-40dB, 40 deg operation range

S11 <-20dB, 4 deg operation range

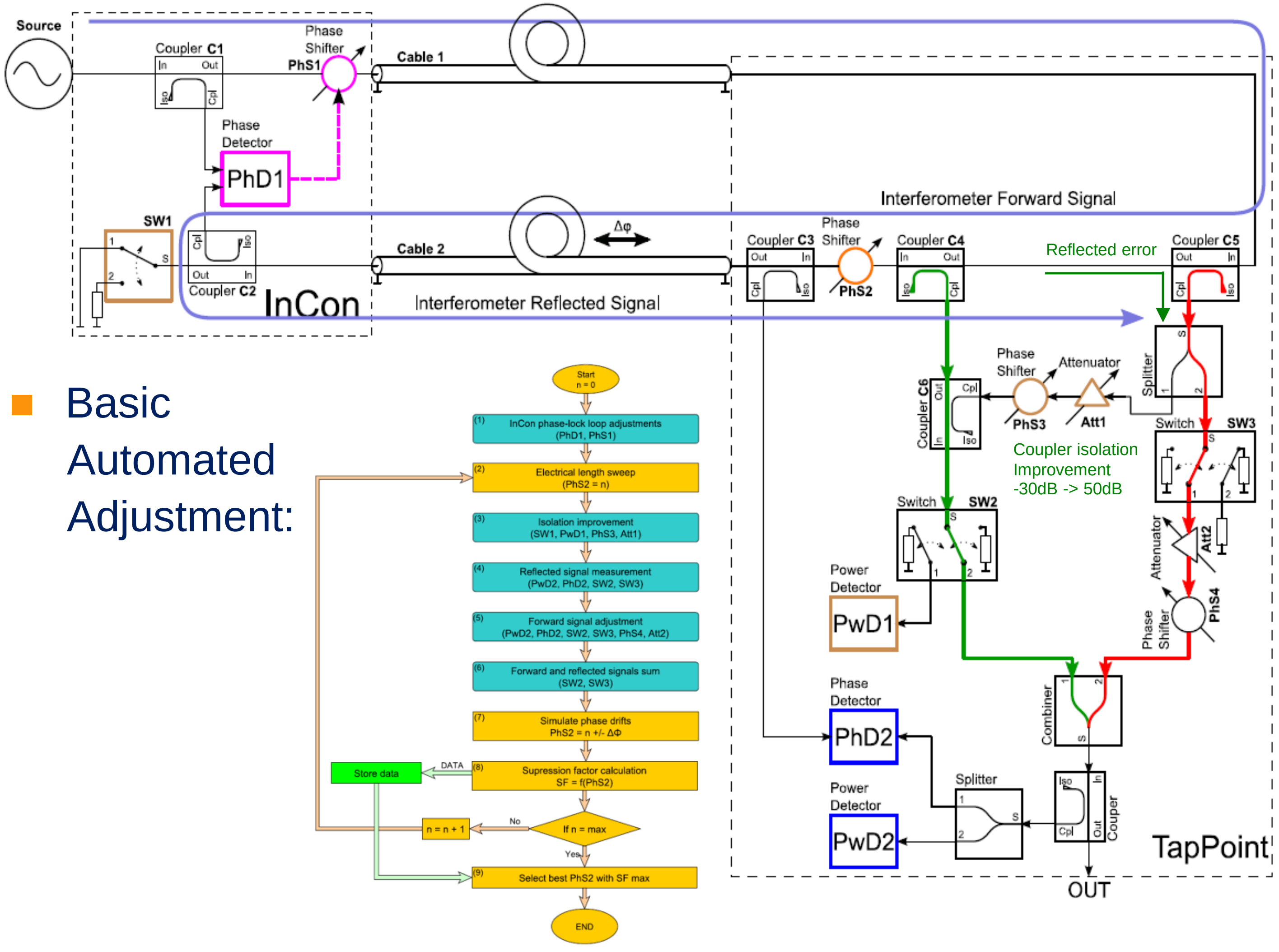

TP1 SF (C5, C6 RL=-25dB, -35dB, -45dB)

- Operation:
  - Cable Phase drifts appear at the combiner inputs with opposite signs
  - Phase of the combined vector not change – no phase drifts at the output
  - Performance limited by cable loss (S11, S21) and coupler isolation
  - Automated adjustment of phases of about ~70 Tap points (XFEL)

RF-Distribution – Interferometer – Laboratory Results

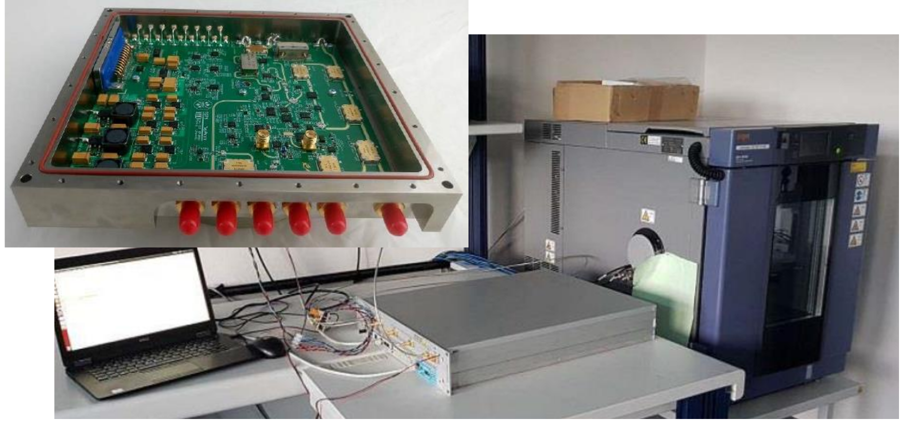
- Simplified RF-interferometer link:

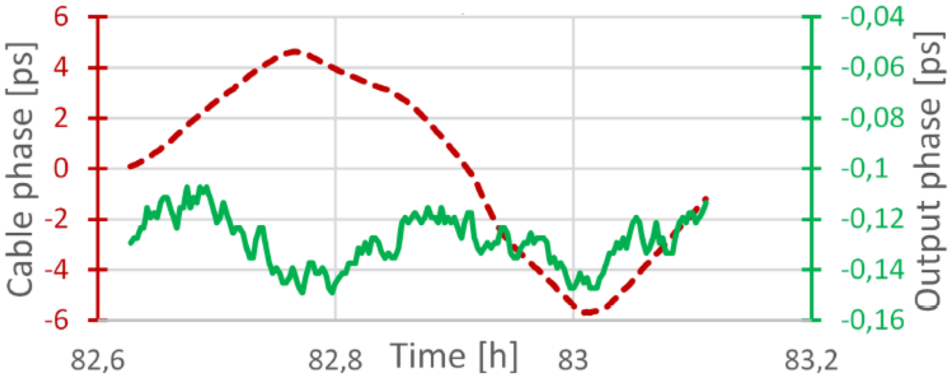
"Phase Drift Compensating RF Link for Femtosecond Synchronization of E-XFEL", D. Sikora, IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 67, NO. 9, SEPTEMBER 2020



- Basic Automated Adjustment:

- Laboratory prototype results:

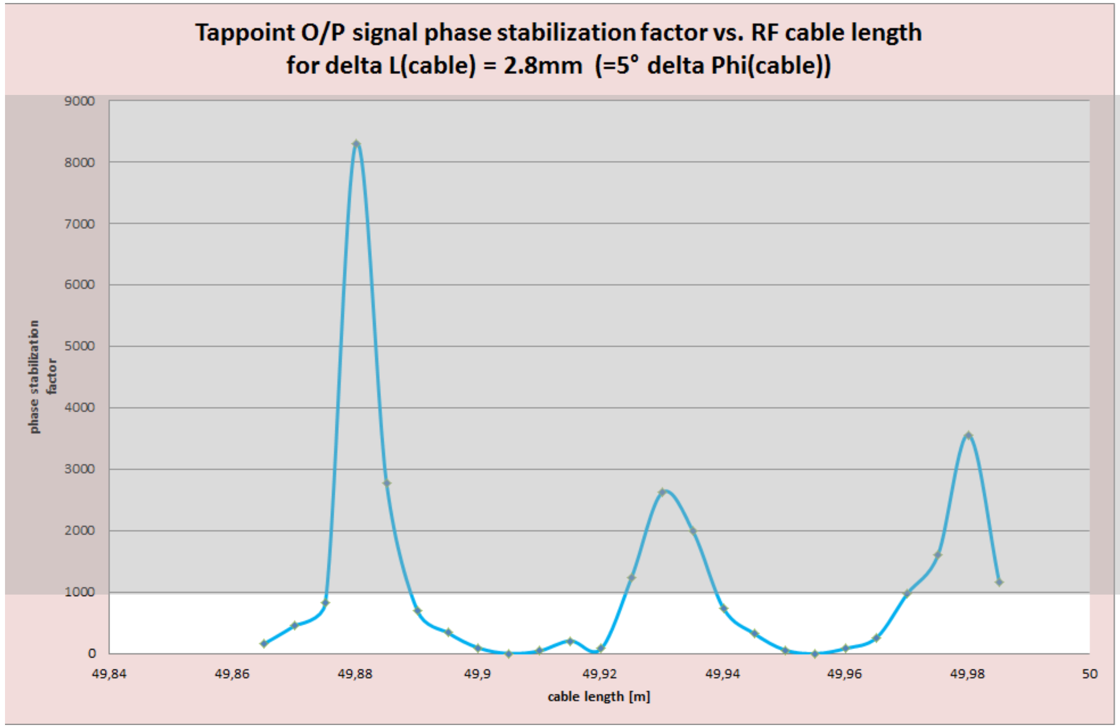


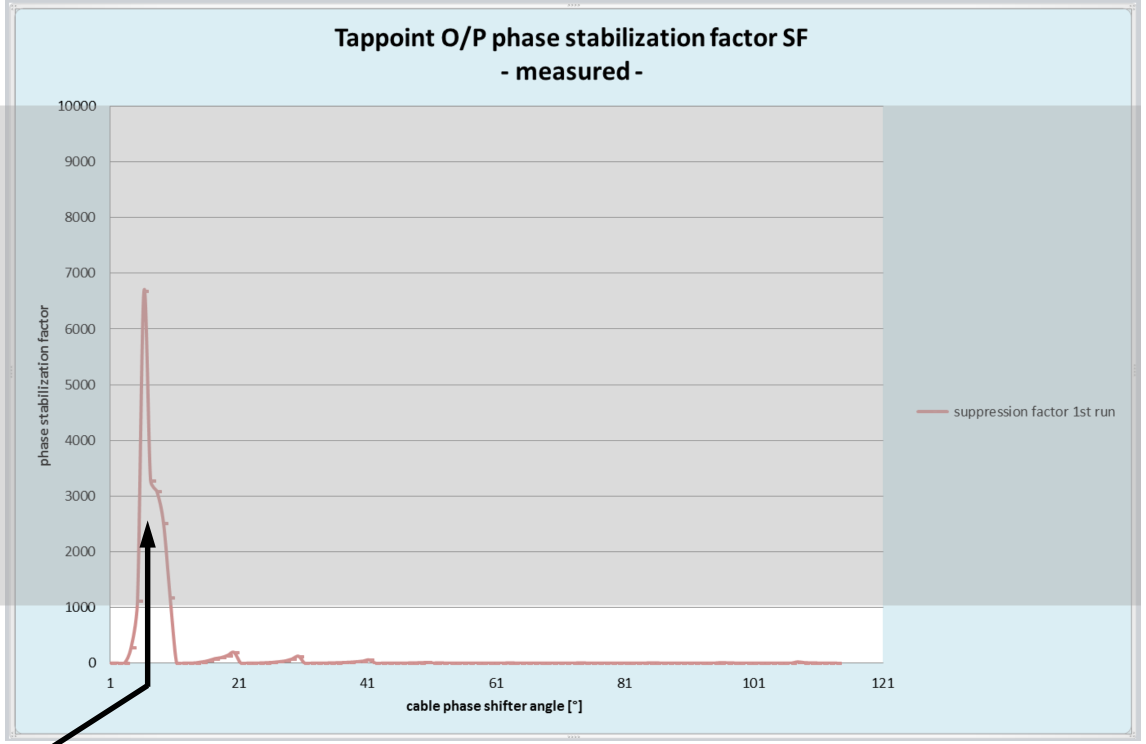


- Suppression of typ.10ps to **<50fs$_{pp}$** (SF=200)
- Setup and out-of-loop detectors not stabilized (neither in T, RH), only 1 chamber @ this time.

RF-Distribution – Interferometer – Challenges for sub-10fs

- Suppression factors (SF) >1000, simulation vs. measurement :



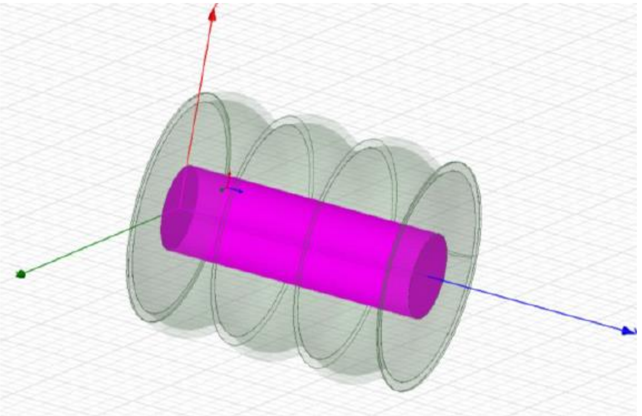


Maintain high SF during long-term operation:

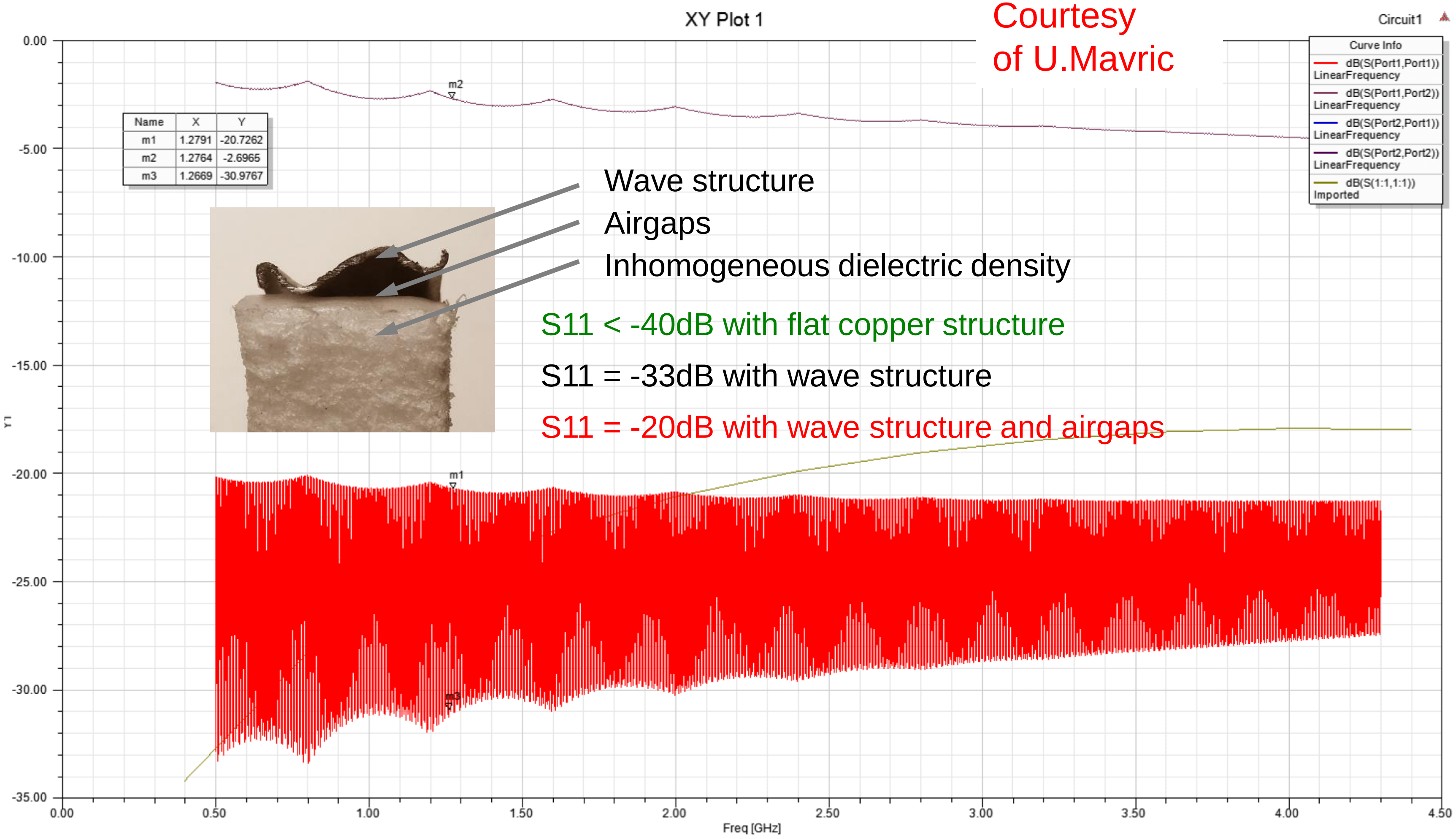
- Simplify setup by using calibrated digital receivers
- RF-cables and connectors should have S11<-35dB
- "On the fly" system recalibration or slow correction
- Requires a group effort for R&D and implementation

Courtesy of
H. Pryschelski, K. Czuba

RF-Distribution – Interferometer – S11 Cellflex cable Limits



vs.



Name	X	Y
m1	1.2791	-20.7262
m2	1.2764	-2.6965
m3	1.2669	-30.9767

Courtesy
of U.Mavric

Wave structure

Airgaps

Inhomogeneous dielectric density

S11 < -40dB with flat copper structure

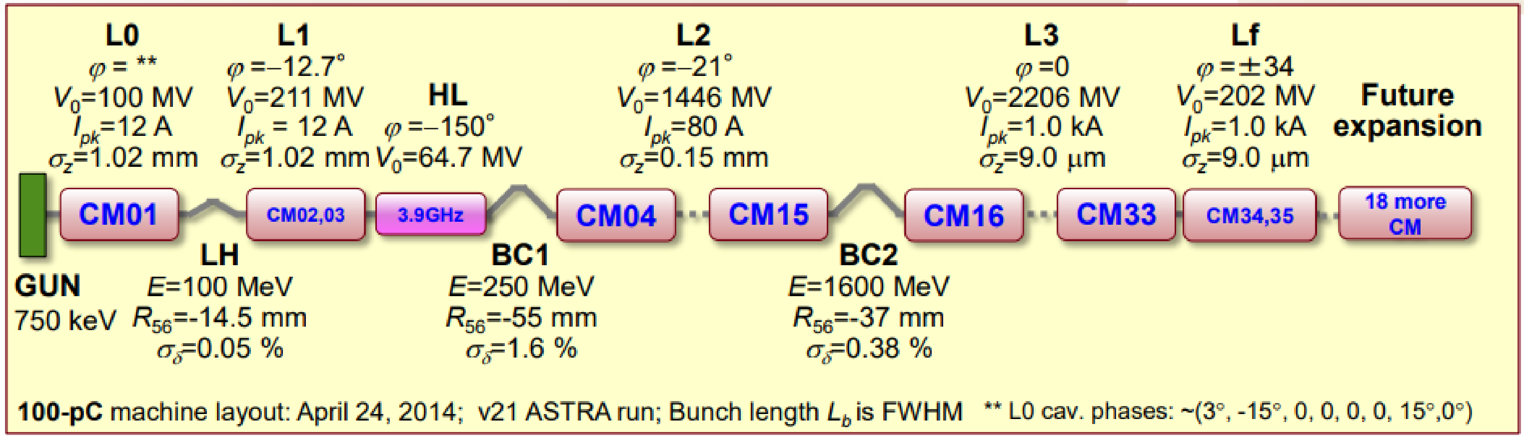
S11 = -33dB with wave structure

S11 = -20dB with wave structure and airgaps

Fig.10: Case c,1/2“ cable extended to 43.2 m. S11@1.3GHz = -20 and IL@1.3GHz= -2.69 dB.

RF-Distribution – Interferometer – first Tests, SLAC - LCLS-II

- LCLS-II structure:



L0
φ = **
V_0=100 MV
I_{pk}=12 A
σ_z=1.02 mm

L1
φ =–12.7°
V_0=211 MV
I_{pk} = 12 A
σ_z=1.02 mm

HL
φ =–150°
V_0=64.7 MV

L2
φ =–21°
V_0=1446 MV
I_{pk}=80 A
σ_z=0.15 mm

L3
φ =0
V_0=2206 MV
I_{pk}=1.0 kA
σ_z=9.0 µm

Lf
φ =±34
V_0=202 MV
I_{pk}=1.0 kA
σ_z=9.0 µm

Future expansion

CM01 **CM02,03** **3.9GHz** **CM04** **CM15** **CM16** **CM33** **CM34,35** **18 more CM**

GUN
750 keV

LH
E=100 MeV
R_{56}=-14.5 mm
σ_δ=0.05 %

BC1
E=250 MeV
R_{56}=-55 mm
σ_δ=1.6 %

BC2
E=1600 MeV
R_{56}=-37 mm
σ_δ=0.38 %

100-pC machine layout: April 24, 2014; v21 ASTRA run; Bunch length L_b is FWHM ** L0 cav. phases: ~(3°, -15°, 0, 0, 0, 0, 15°,0°)

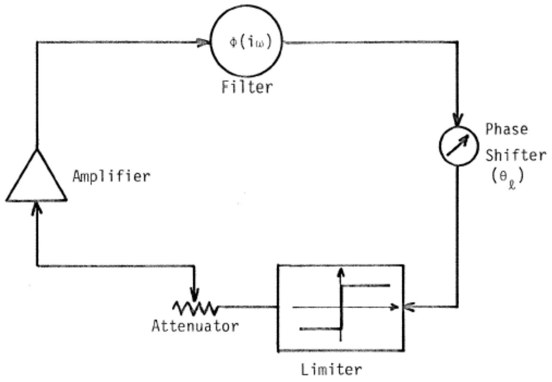
- Phase reference lines (PRL) :

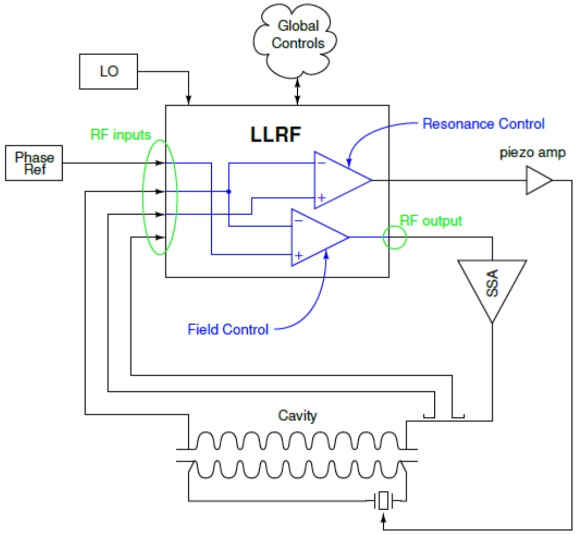
to LLRF, 1300 MHz (REF), 1-5/8” Rigid Line, 650m
1320 MHz (LO)
L0-L1: 6 Couplers, 24 Cav.
L2 : 6 Couplers, 96 Cav.
L3 : 10 Couplers, 144 Cav.
to XTES, 1300MHz (REF)
to LCLS, 476MHz (REF)
to Timing, 1300MHz/7 (REF)

RF-Distribution – Interferometer – first Tests, LCLS-II

- Using self-exited loop (SEL) and detuning equation:

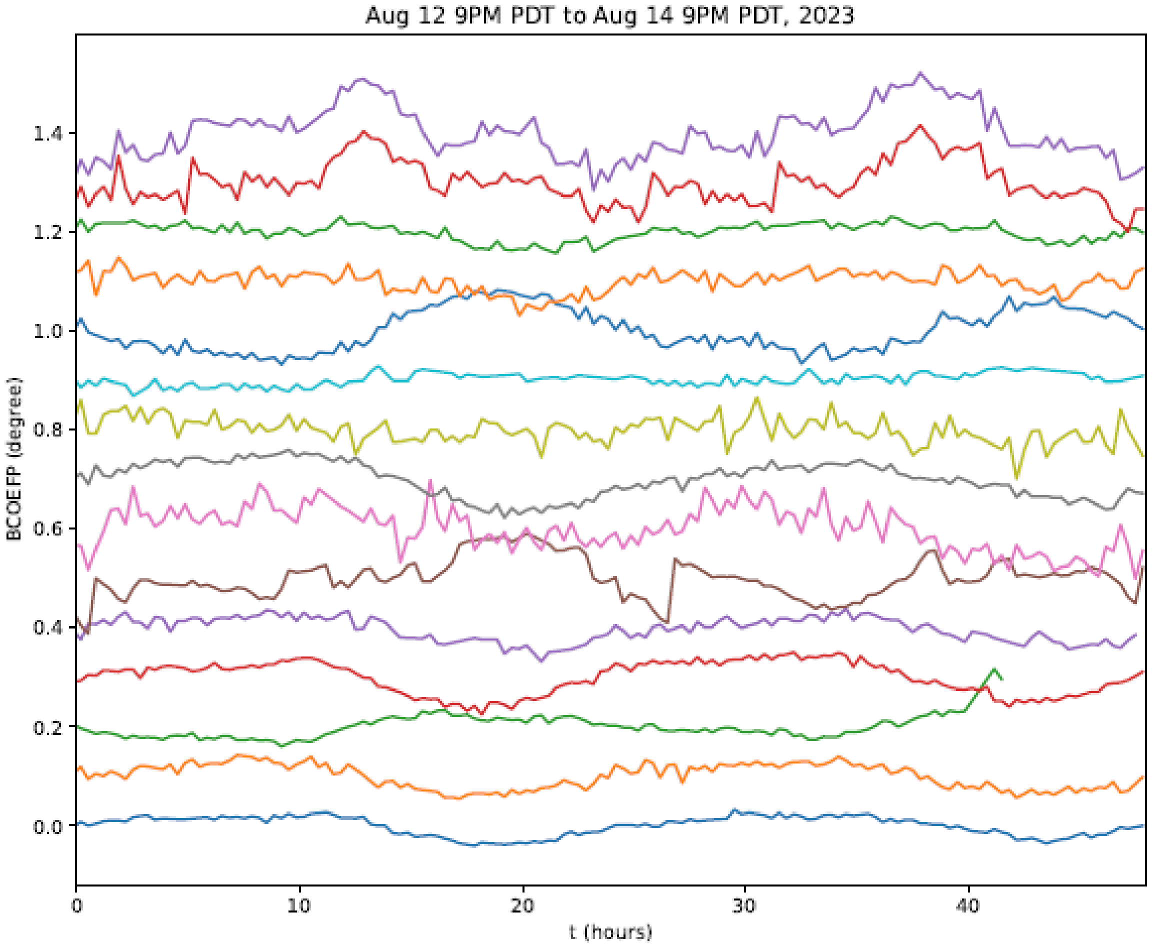
"Drift Observations and Mitigation in LCLS-II RF",
Shreeharshini Murthy, Korea LLRF2023





- Median span drift phase difference is **0.14 deg**.
- It includes PRL + forward and cavity cables to the tunnel within the day-night temperature cycle.
- A residual out of loop test might be helpful.

- Reference to cavity phase

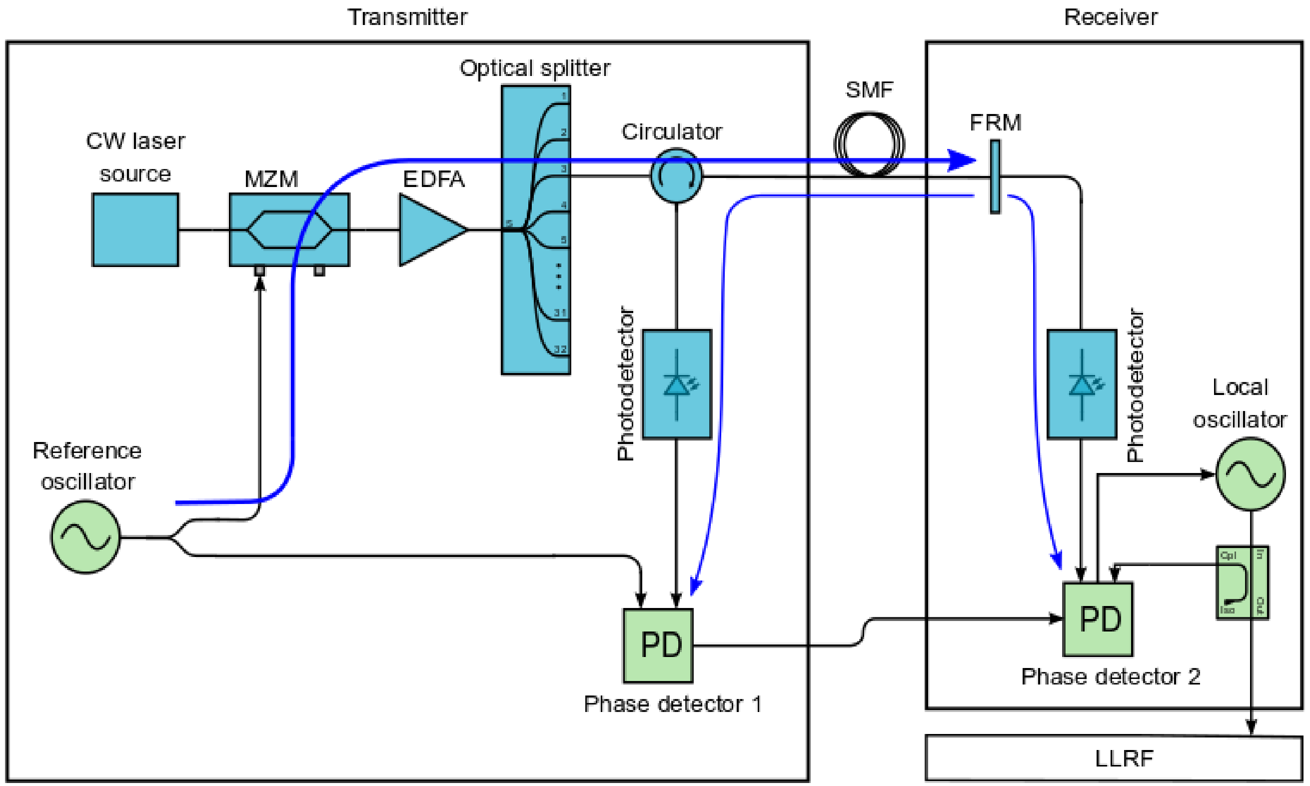


RF-Distribution – in comparison CW optical Links

Courtesy
of S.Jablonski

- Phase drift correction by the reflectometry technique :

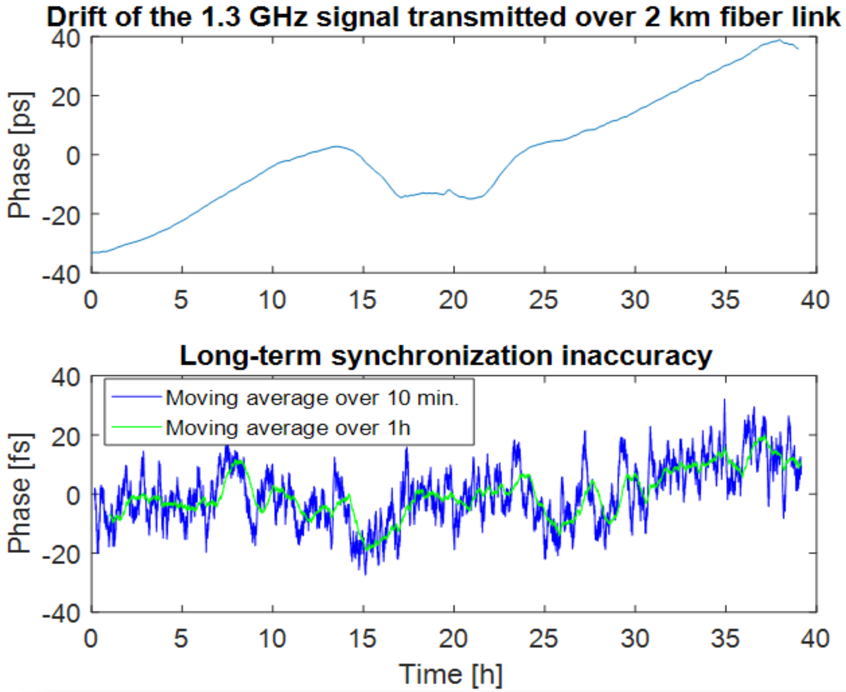
(Standard SMF)
Drift ~40fs/m/K, 2.5 fs/m/%RH



$$\varphi_{drift} = {}^{\varphi_1}/_{2} + \varphi_2$$

$$Drift\ reduction\colon\ {}^{72\ ps}/_{53\ fs} = 1358$$

- Long-term synchronization inaccuracy:



Long-term stability:
< 50 fs_pp for distances < 0.5 km
<100 fs_pp for distances < 2 km

Other good examples:
Libera Sync, Berkeley Sync-Head ✓

Summary and Outlook RF-Oscillators …

- State-of-the-art RF-oscillators have integrated jitters for frequencies >1kHz below 1fs.
- For a minimal beam arrival time jitter, the 1/f-noise of the MO should be further reduced.
  For optical systems the MLO should be improved to avoid un-correlated noise from group delay.
- To avoid spontaneous phase jumps after years from Quarz oscillators, modern MOs should offer the possibility to exchange oscillators “on the fly”.
- Below 1fs, passive and active vibration cancelation methods must be applied.
  Silent racks, fans or water cooling will have an impact on the installation of facilities.

Summary and Outlook RF-Distribution …

- Passive stabilized RF-distribution systems showed a long-term stability in the ps_pp range.
- The short-term stability is relatively easy to achieve and distribute below 10 fs_rms.
  Often small facilities starts with low cost RF-distribution systems and extend to optical systems.

Summary and Outlook RF-Distribution …

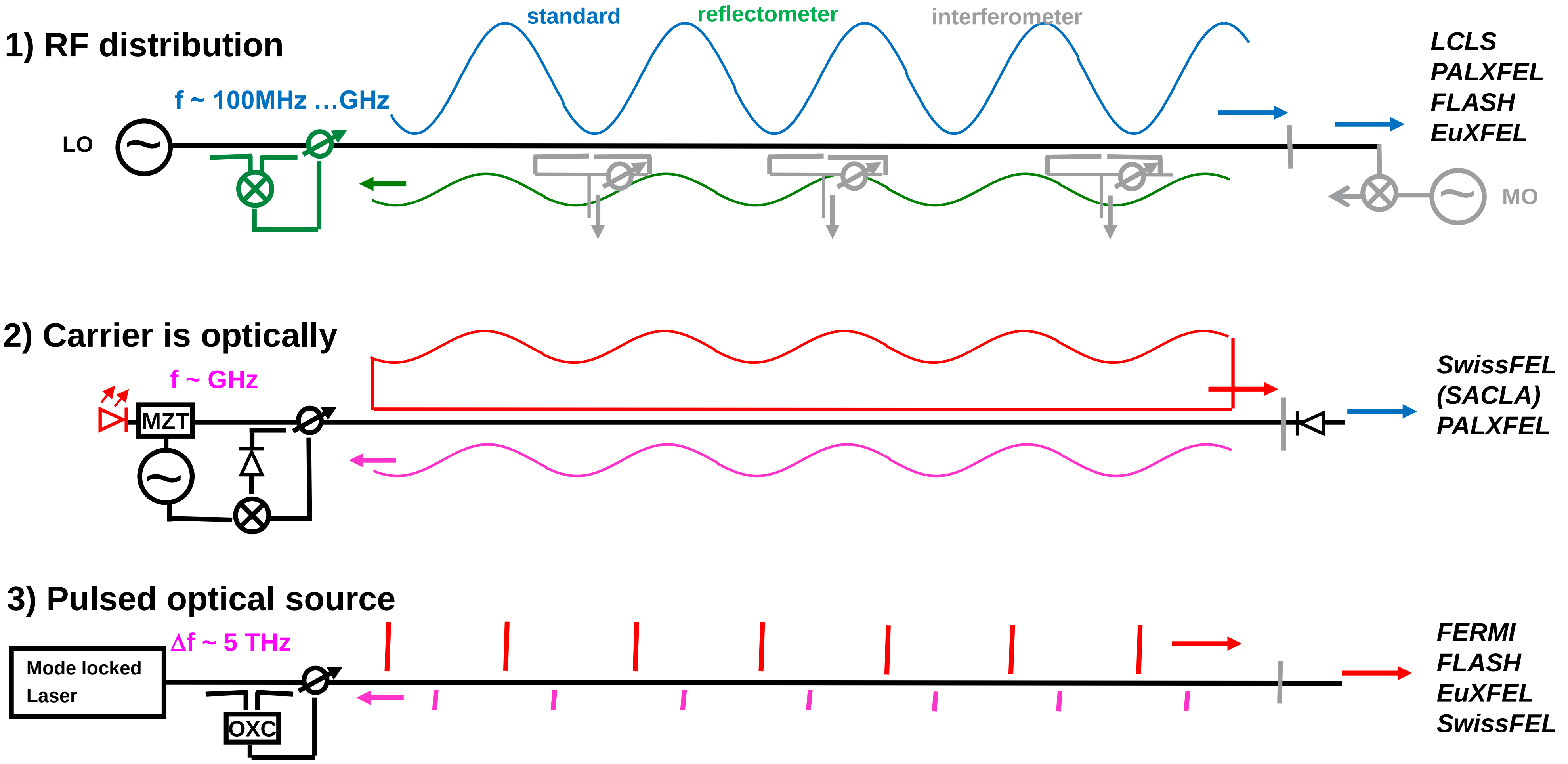
- An optically re-synchronized RF-Distribution combines benefits of robustness and performance.
- State-of-the-art (femtosecond) phase reference lines use active drift stabilization techniques either for RF cables or optical fibers. Optical CW links show results in the 50fs_pp regime. RF based interferometer are either not verified or show similar results in laboratory.
- For sub-10 fs long-term stability, actively compensated RF cables requires suppression factors much higher than 1000 or link lengths in the order of less than 100m.
- Many facilities require an out-of-loop link measurement to verify their link performance precisely.
- RF-cables needs to be characterized in T, RH systematically.
- BB-Feedbacks are needed to remove many tiny residual drifts, e.g. from cavity pickup cables ...

Thanks for your attention!

Different synchronization approaches

Courtesy
of H.Schlarb

- Various approaches:



First proposed:	**J. Kim et al. Proc. of FEL2004 conf., 339-342 (2004)**
Overview:	**M. Xin et al. Light: Science & Applications (2017) 6, e16187;**